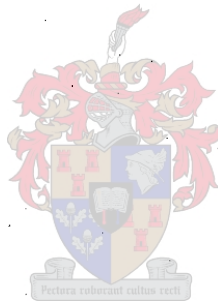


# THE SEDIMENTOLOGY OF THE KALAHARI GROUP IN FOUR STUDY AREAS IN NORTHERN BOTSWANA

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of Science at the University of Stellenbosch.*

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## DECLARATION

I the undersigned hereby declare that the work contained in this thesis is my own original work and has not previously in its entirety or in part been submitted at any university for a degree.

Date: 22/11/93

## ABSTRACT

The Kalahari Group in northern Botswana is subdivided into the Orapa, Makoba and Makgadigadi Subgroups, each with different formations. After the intrusion of kimberlites during the Late Cretaceous, a long period of weathering and erosion set in, followed by the development of hardpan calcrete. The wet climate was replaced by semi-arid conditions, during which the lower Kalahari sediments were deposited. During the Late Cretaceous, major depositional basins developed, each broken up by grabens and horsts. These grabens were filled in by frequent flash floods eroding the horsts, followed by lacustrine sedimentation and finally saline lake conditions. During the Tertiary, a long period of non-deposition, weathering and erosion denudated the landscape by more than 25 m in some areas, forming the Letlhakane Stoneline Formation. Regional calcretes formed subsequently vary in age from Miocene to Pleistocene. In the early Holocene, arid conditions resulted in the formation of linear dune systems, which were degraded, bioturbated and vegetated during subsequent wetter climatic conditions in the Holocene.

## OPSOMMING

Die Kalaharigroep in noord-Botswana word onderverdeel in die Orapa, Makoba en Makgadigadisubgroepe, elk met verskillende formasies. Na die intrusie van kimberliete gedurende die Laat Kryt, het 'n lang tydperk van verwerking en erosie ingetree, gevolg deur die ontwikkeling van oppervlak-kalkreet. Die nat klimaat is vervang deur semi-ariëde toestande, waartydens die onderste Kalaharisedimente afgeset is. Gedurende die Laat Kryt het groot afsettingskomme ontwikkel, wat elkeen deur grabens en horsts opgebreek is. Hierdie grabens is opgevul deur gereelde blitsvloede wat die horsts geërodeer het, gevolg deur lakustriene en uiteindelik soutmeertoestande. Gedurende die Tersiër het 'n lang tydperk van nie-afsetting, verwerking en erosie die landskap met meer as 25 m in sommige gebiede afgestroop, met die vorming van die Letlhakane Stonelineformasie. Regionale kalkrete wat daarna gevorm het, wissel in ouderdom van Mioseen to Pleistoseen. Gedurende die Vroeë Holoseen het droë toestande die ontwikkeling van liniêre duinsisteme tot gevolg gehad, wat tydens natter klimaatstoestande in die Holoseen gedegradeer, omgedolwe en met plantegroei bedek is.

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## (1) INTRODUCTION

### (1.1) General Statement

In the past, work done on the Kalahari Group was mostly of a reconnaissance nature. The paucity of outcrops and the large distances between them, make lateral correlation very difficult, which probably contributed to the Kalahari Group being avoided by geologists. The aim of this thesis is to shed more light on the sedimentology and depositional environment of the Kalahari Group, with emphasis on the Early Kalahari deposits which have been poorly described in the literature. Detailed investigations were therefore made of Kalahari Group sediments in four study areas in northern Botswana (Figs. 1, 2 and 3), to fill at least some of the gaps in our understanding of the Kalahari Group.

### (1.2) Historical background

Numerous papers have been published on the Kalahari sediments. However, most of these papers were either based on geomorphological studies or field work of a reconnaissance nature, sometimes with very little sedimentological evidence. The result is that even the unconsolidated Gordonian Formation, which is probably the most studied lithological unit of the Kalahari Group, remains not fully understood and controversial.

Passarge (1904) originally divided the Kalahari sediments in Botswana into the "Botletle Beds", "Kalahari Limestone", "Kalahari Sands" and "Alluvial Deposits". Maufe (1920) later grouped these beds into the "Kalahari System". This terminology was also adopted by Rogers (1936).

Cahen and Lepersonne (1952) divided the Kalahari sediments of Zaïre into the "Kamina Series", the overlying "Middle Series" and the "Upper Series".

Du Toit (1954) used a two-fold subdivision, viz. the "Kalahari Beds" and the overlying "Kalahari Sands".

Boocock and Van Straten (1962) suggested the term "Kalahari Beds" for the whole Kalahari succession. Grey and Cooke (1977) and Coates et al. (1979) also used this terminology.

Haughton (1963) considered the "Pipe Sandstone" and "Gwampa Chalcedony" of Zimbabwe to be equivalent to the "Botletle Beds" in Botswana.

Smit (1977) established a local stratigraphic succession in the northern Cape Province of South Africa, using borehole records. He placed all the sediments in the "Kalahari Formation" and subdivided it into four units:

- (4) aeolian sands,
- (3) fine grained, clay-rich, calcareous sandstones with silcrete and calcrete,
- (2) red, calcareous clay with layers of fine gravel and coarse sandstone, and
- (1) clay-rich gravel and gravel-rich clay.

The South African Committee for Stratigraphy (SACS, 1980) defined the "Kalahari Group" and proposed the following subdivision:

- (4) Gordonias Sand Formation - Aeolian sand, pan sediments, calcrete and diatomaceous limestone
- (3) Eden Sandstone Formation - Calcareous sandstone, gritstone and conglomerate
- (2) Budin Clay Formation - Calcareous gravelly clay
- (1) Wessels Gravel Formation - Basal clayey gravel.

Although the established term "Kalahari Group" is used in this study, a different stratigraphic succession is proposed for the study areas in northern Botswana, as the work of Smit (1977) is an over-simplification of the sedimentological record. Moreover, care should be taken in correlating the stratigraphic sequence of different areas as far apart as South Africa and northern Botswana with one another.

A non-exhaustive list of publications on the Kalahari includes (in topical and chronological order):

Kalahari geology in general:

Passarge (1904), Maufe (1920, 1939), Cahen and Lepersonne (1952), Du Toit (1954), Mabbutt (1955), Boocock and Van Straten (1962), Money (1972), Smit (1977), Coates et al. (1979) and Thomas (1987).

Kalahari geomorphology in general:

Helgren (1978), Lister (1979), Mallick et al. (1981), Hövermann (1988), Shaw et al. (1988), Thomas and Shaw (1988) and Lancaster (1989).

Kalahari sand and dunes:

Rogers (1936), Bond (1948), Poldervaart (1957), Grove (1969), Goudie (1970), Binda and Hildred (1973), Cahen and Moeyersons (1977), Savat and Poesen (1977), Moeyersons (1978), Lancaster (1980), Buckley (1981), Lancaster (1981), Goudie and Thomas (1986), Lancaster (1986a, 1987a, 1987b), Thomas (1987), Thomas and Martin (1987), Lancaster (1988), Thomas (1988), Eriksson et al. (1989) and Thomas (1989).

Pans:

Flint and Bond (1968), Baillieul (1975), Lancaster (1978), Baillieul (1979), Bruno (1985), Goudie and Thomas (1985), Lancaster (1986b) and Shaw and Thomas (1989).

Duricrusts of the Kalahari:

Netterburg (1978, 1980), Watts (1980), Summerfield (1982), Goudie (1983), Summerfield (1983) and Shaw and De Vries (1988).

Makgadikgadi lake deposits:

Grey (1976), Grey and Cooke (1977), Ebert and Hitchcock (1978), Heine (1978b), Cooke (1979), Cooke and Verstappen (1984), Helgren (1984), Shaw (1985, 1988).

Caves in the Kalahari:

Cooke (1975a, 1975b), Cooke and Verhagen (1977), Pickford and Mein (1988) and Brook et al. (1990).

Kalahari palaeoclimate:

Butzer et al. (1978), Heine (1978a), Lancaster (1979), Van Zinderen Bakker (1980), Heine (1982), Butzer (1984), Cooke (1984), Rust (1984), Shaw and Cooke (1986), Tyson (1986) and Deacon and Lancaster (1988).

Kalahari tectonics:

Reeves (1972) and Reeves and Hutchings (1975).

(1.3) Study areas

Detailed field work was carried out in four study areas in northern Botswana (Orapa-Letlhakane, South Sua Pan, Nata and Mmashoro) (Figs. 1, 2 and 3). Over the rest of northern Botswana, a study of Landsat TM images and work of a reconnaissance nature was done.

The study consisted of: mapping; drilling, and re-interpretation of existing borehole information; logging of profiles in outcrops; utilising borrow-pits for correlation, and remote sensing through the use of SPOT, Landsat TM and aerial photographs. Petrographic work was also conducted on selected samples from the study areas.

The maps of the study areas were drawn with the available information. In many cases, as no outcrops exist in the field due to sand cover, remote sensing was used to define lithological boundaries. With more drilling information, some of the boundaries may need to be revised.

(1.4) Population

The major towns and villages in the different study areas are:

Orapa and Letlhakane (Study area 1) (Fig. 3c),  
Mosu (Study area 2) (Fig. 3d),  
Nata (Study area 3) (Fig. 3e) and  
Mmashoro (Study area 4) (Fig. 3f).

The Orapa and Letlhakane open-cast diamond mines are the biggest employers in all four study areas. The other settlements are villages housing people engaged in near-subsistence cultivation and cattle rearing on lands and at cattle posts in the surrounding areas.

### (1.5) Climate

The study areas in northern Botswana have a semi-arid climate, with virtually all the rain falling in the warmer months (October - April). Rainfall is usually less than 500 mm per year and in the form of thundershowers. The quantity of rainfall decreases from the north-east to the south-west of Botswana, so that the Nata Area (Study area 3) receives more rain than the other study areas. Humidity is generally low, with evaporation far exceeding precipitation.

The summer months are warm to hot, with occasional frost during the colder months. Strong winds occur in August and September.

### (1.6) Vegetation

The vegetation of the study areas can be classified into three types:

- (a) Woodland (Single-stemmed trees higher than 2 metres and multi-stemmed trees or shrubs higher than 5 metres),
- (b) Shrubland (Single-stemmed trees lower than 2 metres and multi-stemmed trees or shrubs lower than 5 metres), and
- (c) Grassland (Grasses) (Grey, 1976).

The woodlands usually cover areas in the vicinity of scarps, rivers, dolerite dykes and faults, as well as areas where there is a shallow soil cover over basement rocks. Common species include: Marula (*Sclerocarya birrea*), Knob thorn (*Acacia nigrescens*), Camel thorn (*Acacia erioloba*), Leadwood (*Combretum imberbe*), Mopane (*Colophospermum mopane*), Silver cluster-leaf (*Terminalia cericea*), Thorny cluster-leaf (*Terminalia prunoides*), Shepherd's tree (*Boscia albitrunca*), Commiphora species and Combretum species.

Shrublands cover most of the remainder of the area. Stunted Mopane shrubs are conspicuous in the palaeo-pans in the South Sua Pan Area (Study area 2). Common shrubland species include: Sickie bush (*Dichrostachys cinerea*), Grewia species like the Velvet raisin and Rough-leafed raisin, Russet bushwillow (*Combretum hereroense*), and Mopane (*Colophospermum mopane*). The grass cover consists of *Cenchrus ciliaris*, *Dichanthium papillosum*, *Digitaria milaniana* and *Eragrostis* species.

Grasslands are found in and around the Makgadikgadi Pan complex. Common grassland species on the edge of Sua Pan include: *Aristida meridionalis*, *Cymbopogon* species, *Heteropogon contortus*, *Odyssea paucinervis* and *Sporobolus spicatus*.

Certain types of vegetation give indications of the underlying soil conditions, for example, the Silver cluster-leaf and Camel



thorn prefer sandy soils with a low pH, and the abundant presence of these trees is usually a good indication of deep sandy soils.

On the other hand, the Thorny cluster-leaf and Transvaal sesame bush (*Sesamothamnus lugardii*) prefer clay-rich soils and can be found in abundance on the edges of the Makgadikgadi pans.

Dolerite dykes in the study areas are often calcrete-capped and support a dense vegetation cover consisting of: Sickie bush, *Grewia* species like the Velvet raisin and Rough-leaved raisin, Knob thorn and Mopane. The dense vegetation cover makes dolerite dykes easy to recognize with remote sensing techniques, such as SPOT and Landsat imagery.

In the study areas, faults also support dense vegetation which facilitate their identification on SPOT images and aerial photographs.

### (1.7) Geomorphology

A detailed geomorphological description of northern Botswana can be found in Mallick et al. (1981).

#### Orapa-Letlhakane Area (Fig. 3c) and South Sua Pan Area (Fig. 3d)

These study areas lie to the south of the Makgadikgadi Pans Complex. Southwards from Sua Pan, the land rises gently until the fault controlled Mosu scarp is reached. At a point some 16 km east of Mosu village, the maximum elevation on top of the scarp is 91 m above the level of Sua Pan. From the top of the scarp the land rises gently to the south.

The main drainage of the Orapa-Letlhakane Area (Fig. 3c) and South Sua Pan Area (Fig. 3d) is towards the north and north-west. Ephemeral rivers, which drained into the Makgadikgadi Pan Complex, were probably established during wet periods in the Pleistocene. During exceptionally wet years these rivers still flow.

Some of the rivers, however terminate at palaeo-strandlines (beach ridges), indicating the former flow of these rivers into the large lakes that existed at the time.

The largest river in the Orapa-Letlhakane Area (Fig. 3c) and South Sua Pan Area (Fig. 3d), is the fault-controlled Letlhakane River, which shows meanders in its former floodplain. A large area near Orapa is covered by alluvium deposited by this river.

In the South Sua Pan Area (Fig. 3d) a number of palaeo-pans of probable Pleistocene to Holocene age, were recognized on SPOT

images and investigated in the field. In most cases, the palaeo-pans overlies outcrops of Ntane sandstone. Those investigated comprise one to two metres of vertisol overlying the Letlhakane Stoneline Formation (LSF) (See section 5.2.3). Stunted Mopane shrubs grow on the palaeo-pans, which are normally surrounded by tall trees.

#### Nata Area (Fig. 3e)

In this study area all the rivers drain towards the west, into Sua Pan. A number of palaeo-rivers were found which had previously drained into the Makgadikgadi lakes during wet periods in the past (Fig. 3e). The Nata River, which still flows today, has formed a large delta where it enters Sua Pan.

The landscape is relatively flat, with a few shoreline features such as beach ridges and beach ridge complexes up to 3 metres high. In both the south-western and northern parts of the Nata Area, a beach ridge complex has resulted in the formation of a sand spit, projecting into the pan.

#### Mmashoro Area (Fig. 3f)

The three most conspicuous geomorphic features in this area are:

- (a) the north-easterly draining Moenyenana River and its headwaters,
- (b) the scarp, which forms the present limit to the distribution of the Early Kalahari (Orapa Subgroup) sediments, and
- (c) the NE trending dunes.

The scarp is thought to be the result of cut-back by tributaries of the Limpopo River (such as the Moenyenana River) since the Miocene, due to tectonic-activated base level lowering of the lower Limpopo.

## (2) STRATIGRAPHY

Four major lithological units were recognized in the study areas. These comprise Archaean metamorphic and granitoid rocks, the Palaeozoic to Mesozoic Karoo strata, the post-Karoo intrusives and the Mesozoic to Cainozoic Kalahari sediments.

### (2.1) Basement Complex

Outcrops of the Archaean Basement Complex are restricted to the Nata Area (Fig. 3e). The dominant lithologies are banded, granoblastic and porphyroblastic gneisses, amphibolite, and metasediments such as quartzite. The gneisses are intruded by pink equigranular granite and pegmatitic veins of quartz and feldspar.

### (2.2) Karoo Supergroup

#### (2.2.1) Tlapana Formation

The Tlapana Formation is the uppermost formation of the Ecca Group in Botswana (Smith, 1984). Outcrops of the Tlapana Formation can be found in the South Sua Pan Area (Fig. 3d). The Tlapana Formation is essentially composed of carbonaceous mudstone and coal seams, with subordinate grey to brown sandstone, siltstone and mudstone.

The Tlapana Formation has characteristics of deltaic deposition under cool temperate conditions. Peat that was established on floodplains resulted in the Ecca coal seams (Smith, 1984).

#### (2.2.2) Tlhabala Formation

The Tlhabala Formation can probably be correlated in age with the Beaufort Group (Smith, 1984). Outcrops of the Tlhabala Formation occur in the South Sua Pan Area (Fig. 3d). The Tlhabala Formation consists of red, green and grey, calcareous siltstone and mudstone.

The Tlhabala Formation is interpreted to have been laid down in an open-water lacustrine depositional environment (Smith, 1984).

### (2.2.3) Lebung Group

The Lebung Group includes all the clastic "red bed" formations deposited unconformably on the Tlhabala Formation (Smith, 1984) and its equivalent in the main Karoo Basin are the Elliot and Clarens Formations. The Lebung Group is in turn unconformably overlain by the Drakensberg Lava Group.

The Lebung Group is split into the lower, waterlain Mosolotsane Formation and the unconformably overlying Ntane Sandstone Formation (Plates 1 and 2). Outcrops of both formations of the Lebung Group occur in the Orapa-Letlhakane Area (Fig. 3c) and South Sua Pan Area (Fig. 3d).

While the Mosolotsane Formation was deposited under seasonal to ephemeral fluvial conditions, aeolian with only minor fluvial activity predominated during the deposition of the Ntane Sandstone Formation (Smith, 1984).

#### (2.2.3.1) Mosolotsane Formation

The Mosolotsane Formation is the age equivalent of the Elliot Formation (SACS, 1980) in South Africa. The formation consists of reddish gritstone, sandstone, siltstone and mudstone (Plate 1). Grey-green reduced spots or bands are common in the siltstone and mudstone. Reducing depositional environments also resulted in some deposits of dark to pale green Mosolotsane mudstone and siltstone in the South Sua Pan Area (Fig. 3d).

#### (2.2.3.2) Ntane Sandstone Formation

The Ntane Sandstone Formation is the age equivalent of the Clarens Sandstone Formation (SACS, 1980) in South Africa. The formation consists of large scale cross-bedded, aeolian sandstone, with subordinate fluvial siltstone, sandstone, gritstone and conglomerate (Plates 1 and 2).

### (2.2.4) Drakensberg Lava Group

K-Ar age dating puts the age of the Drakensberg Lava Group at  $180 \pm 10$  Ma, which agrees with ages determined for Karoo basalts in central South Africa ( $187 \pm 7$  Ma) (Smith, 1984). Outcrops of the Drakensberg Lava Group occur in the Orapa-Letlhakane Area (Fig. 3c), South Sua Pan Area (Fig. 3d) and Nata Area (Fig. 3e) as well as the Mmashoro Area (Fig. 3f). In the study areas, the Drakensberg Lava Group comprises a series

of tholeiitic basalt flows, each up to 30 metres thick, in which an upper and lower amygdaloidal zone and a massive central zone can be distinguished.

In some localities, such as the Letlhakane Mine (D/K 1 kimberlite) (Fig. 3c), thin (less than 2 metres thick), baked sandstone and siltstone lenses occur between some of the basaltic lava flows.

Outcrops of Drakensberg basalt show variable weathering; from weathered green and reddish purple to dark, greenish grey when fresh. Investigations of outcrops and more than 50 boreholes in the study areas, revealed that where the basalt is still covered by Orapa Subgroup sediments, and therefore protected from present day erosion, the basalt is often weathered down to about ten metres from its upper contact. The Drakensberg basalt also has a calcrete capping (see section 2.5) which is eroded away in some places by the Orapa Subgroup sediments.

### (2.3) Dolerites

Within a generally WNW trending, complex fracture pattern, an extensive system of Late or post-Karoo dolerite dykes and sills can be recognized (Orapa-Letlhakane Area (Fig. 3c) and South Sua Pan Area (Fig. 3d)). The dolerite dykes form part of the dyke swarm (Coates et al., 1979) that extends over the whole length of northern Botswana (a distance of more than 600 kilometres).

Dolerite emplacement was controlled by a pre-existing, WNW fracture pattern in the Karoo strata (Coates et al., 1979). A number of dolerite dykes in the study areas have coincident faults of Kalahari age, indicating the re-activation of the original fractures after dolerite emplacement. Figures 4 and 5 show the relationship between faults and dolerite dykes in the Orapa-Letlhakane Area (Fig. 3c) and South Sua Pan Area (Fig. 3d). A 140 Ma age was determined for dolerite dykes near Serowe (Fig. 1) (Smith, 1984).

Strong intrusive force associated with dyke emplacement is suggested by the steep dips of Karoo strata adjacent to some dykes in the South Sua Pan Area (Fig. 3d).

The hard dolerites weather positively to form ridges and hills, often with thick calcrete cappings as a result of calcium release from the dolerite during weathering.

#### (2.4) Kimberlites

A large number of kimberlites forming part of the Orapa Kimberlite Province, are present in the Orapa-Letlhakane Area (Fig. 3c). The two largest kimberlites, A/K 1 (Orapa Mine) and D/K 1 (Letlhakane Mine) are currently being mined for diamonds. Isotope dating gave a Cretaceous age (~ 90 Ma) for kimberlite emplacement in this area (Rayner et al., 1991).

#### (2.5) Kwari Calcrete Formation

Investigations in the Orapa-Letlhakane Area (Fig. 3c) have shown that there was strong erosion during the Cretaceous period following the emplacement of kimberlites at ~ 90 Ma. Diamondiferous soils around the Orapa kimberlite (A/K 1) suggest that between 50 and 100 metres of sediments have been removed by erosion (Rayner et al., 1991). Most of the erosion is interpreted to have taken place in the Cretaceous as the Mmashoro Formation sediments (see section 2.6) in the vicinity of Orapa are interpreted as low energy lacustrine sediments (see section 5.2.1) that caused negligible erosion of the underlying lithologies.

Some of the erosion probably took place during the formation of the Letlhakane Stoneline Formation (LSF) (see section 5.2.3) in the Tertiary. However, calculations (section 5.2.3) suggest that the landscape was lowered by a minimum of 25 metres and a maximum of 50 metres in the Orapa-Letlhakane area in order to have produced the volumes of kimberlitic heavy minerals recovered from the LSF around the Letlhakane kimberlites (D/K 1 and D/K 2). This falls short of the 50 to 100 metre erosion estimated for the A/K 1 kimberlite near Orapa (Fig. 3c). The rest of the erosion is therefore interpreted to be Cretaceous in age. This erosional period was, in turn, followed by a long period of non-deposition, during which an initial period of deep weathering (described in section 2.2.4) was followed by the formation of a hardpan calcrete (with minor silcrete) that capped the landscape (Fig. 6).

This Cretaceous calcrete is called the Kwari Calcrete Formation (after a village in the South Sua Pan Area) and it overlies rocks of the Karoo Supergroup, post-Karoo dolerite dykes and kimberlites of the Orapa Kimberlite Province and is eroded and overlain by the ~ 75-70 Ma old Kalahari Group. Outcrops of the Kwari Formation can be found a few hundred metres south of A (Orapa-Letlhakane Area (Fig. 3c)). Numerous boreholes and pits in the Orapa-Letlhakane Area (Fig. 3c) and South Sua Pan Area (Fig. 3d) have intersected the Kwari Formation.



The Kwari Formation is a hardpan calcrete near its upper contact and it grades into the underlying bedrock which could be weathered basalt, dolerite or kimberlite, as mentioned above. The calcrete has a maximum thickness of 1.5 m in the study areas.

## (2.6) Kalahari Group

A detailed discussion of Kalahari stratigraphy will be given in the author's PhD thesis. The following summary of Kalahari stratigraphy serves as an introduction to the sedimentological studies which form the main part of this thesis.

The Kalahari Group is subdivided by this author into three lithostratigraphic subgroups, namely the Orapa Subgroup (named after the town in Fig. 3c), Makoba Subgroup (named after a village and veterinary camp in the South Sua Pan Area) and Makgadikgadi Subgroup (different sections in and around the Makgadikgadi Pans of northern Botswana).

In the four study areas, the Orapa Subgroup comprises the Mmashoro Sandstone Formation only, but work done outside the four study areas indicated the probability that the subgroup will eventually be divided into more formations. According to section 3.8 on page 649 in SACS (1980) this classification is then justified. The Makoba Subgroup is made up of the Letlhakane Stoneline Formation, calcretes and the Gordonina Formation (see section 3). The Early Kalahari age sediments of the Orapa Subgroup are consolidated and separated from the softer Late Kalahari age sediments of the Makoba Subgroup by the Letlhakane Stoneline (see section 5.2.3 and Fig. 6). This stoneline can easily be recognized in outcrops and boreholes and forms an excellent marker horizon.

The subdivision of the Makgadikgadi Subgroup falls beyond the scope of this thesis and it is only briefly described (section 3), but work done outside the present study areas has shown that the Makgadikgadi Subgroup can be subdivided into a number of formations. As will be explained in section 3, the four study areas in northern Botswana lie close to the margins of a major Kalahari basin and represent, especially as far as the younger Kalahari sediments are concerned, a compressed sequence. A detailed stratigraphy devised for this marginal area is therefore not deemed appropriate at this stage.

For the sake of informal use the Kalahari Group is also chronostratigraphically subdivided into Early Kalahari sediments which comprise the Orapa Subgroup and Late Kalahari sediments which comprise the Makoba Subgroup and Makgadikgadi Subgroup.

The age of the Kalahari Group in Botswana remains problematic due to the general lack of fossils, rocks that are not suitable for dating and the problems in correlating previously dated deposits on the margins with the main Kalahari Basin, e.g. the gravel in the Koa River in which Miocene gravels were found (Malherbe et al., 1986).

The deposition of the Kalahari Group is postulated to have started at about 75-70 Ma. Apatite fission track dating in southern Africa shows distinct episodes of cooling of the crust at about 100 to 90 Ma (a period during which a number of kimberlites intruded) and more importantly at ~ 75-70 Ma, when significant intra-plate deformation also took place along the old (Pan African) Damara Metamorphic Belt or second-order plate boundary, similar to that predicted for the opening of the south Atlantic (Brown, 1990). The cooling is assumed to be the result of discrete episodes of erosion. According to Brown (1990) there appears to be a casual link between the period of major plate reorganization at ~ 70-75 Ma during the opening of the south Atlantic (Unternehr et al., 1988) and the denudational and tectonic history of the continental interior. The apatite fission track analysis therefore suggests major erosional episodes at about 100 to 90 Ma and at about 75 to 70 Ma in southern Africa. The strong tectonic influence on Orapa Subgroup deposition, can clearly be seen in the Mmashoro and South Sua Pan areas. It is interesting that there is evidence for a major marine regression around the southern African coast at ~ 70 Ma when the sea level dropped to 500 metres below present (M. Bremner and J. Rogers pers. comm., 1992). The dating of tree fossils from a palaeoriver in the northern Cape Province, close to the Botswana border, whose source was cut off by tectonic movement, gave ages of ~ 85-75 Ma (Partridge pers. comm., 1992). Clast types in the palaeoriver favours a source to the north-west. If this was indeed a pre-Kalahari river, a 75-70 Ma age for the Kalahari tectonic event (that severed the river from its source) seems feasible. However, fossil wood with a possible Tertiary age that was also found in the palaeoriver complicates the issue.

The postulated tectonic event at ~ 75-70 Ma, is thought to have broken up the southern African continent into horst and graben structures. Vertical displacement along faults was generally of the order of tens of metres in the study areas in northern Botswana. Tectonic movement was followed by the erosion of the horsts and rather rapid in-fill of the grabens by saline lake deposits in a semi-arid climate.

The deposits found in the grabens of the study areas consist of alluvial fan conglomerates in the close proximity of faults, grading downslope into ephemeral braided stream sediments. The ephemeral braided stream sediments in turn grade downslope and upwards into ephemeral lake deposits (Figs. 6 and 7).

As mentioned above, the Late Kalahari age Makoba Subgroup consists of the Letlhakane Stoneline Formation (LSF), overlain



by calcretes and the Gordonia Formation (see section 3). The gravelly LSF formed over a long period of time during which no deposition took place and erosion lowered the landscape by tens of metres. The type section for the LSF occurs at the Letlhakane Mine, although numerous other exposures occur in the different study areas, such as at borrow pit 14 in the South Sua Pan Area (Fig. 3d). The age of the LSF is problematic since it could still be forming today in some places. It possibly first started forming in the Palaeocene.

Absolute dating will be needed to confirm the dates given above, which has been hampered by the lack of vertebrate fossils. Part of the Makoba Subgroup can be dated with techniques such as thermoluminescence (TL).

### (3) THE KALAHARI GROUP SEDIMENTS AND THEIR DEPOSITIONAL ENVIRONMENTS

The characteristics of the Kalahari sediments discussed in this section are treated in more detail in the study areas described in section 4. The Kalahari Group is subdivided into the Orapa Subgroup and the Makoba Subgroup, the contact being placed at the base of the Letlhakane Stoneline Formation (Fig.6). As mentioned previously, the Makgadikgadi Subgroup falls beyond the scope of this thesis and is only briefly described. All the Early Kalahari sediments described below form part of the Mmashoro Sandstone Formation, which is named after the main village in the fourth study area (Fig. 3f).

#### (3.1) ORAPA SUBGROUP:

##### (3.1.1) Mmashoro Sandstone Formation

##### (3.1.1.1) Dikara Conglomerate Member

Near the western (Mabbutt, 1955) and southern (Smit, 1977) margins of the Early Kalahari sedimentary succession, basal conglomerates, up to 100 metres thick, were described as the Budin Formation in the literature. However, in the four study areas in northern Botswana, basal conglomerates form only a minor component of the Kalahari Group. The basal conglomerates are impersistent in their distribution and usually confined to the close proximity of faults, where they represent proximal facies of the Mmashoro Formation (section 5.3.1). This basal conglomerate is called the Dikara Member after a village in the Mmashoro Area.

Basal conglomerates of the Dikara Member were only seen in the Orapa-Letlhakane Area (Fig. 3c, section 5.2.1), South Sua Pan Area (Fig. 3d, section 5.3.1) and the Mmashoro Area (Fig. 3f, sections 5.5.2 and 5.5.4).

The conglomerate clasts reflect the local geology in the study areas. In the Orapa-Letlhakane Area (Fig. 3c, section 5.2.1, profile A) and Mmashoro Area (Fig. 3f, section 5.5.4) the conglomerate clasts are almost entirely calcrete clasts in a sandy matrix, derived from the underlying pre-Kalahari calcrete (section 2.5) that caps the Drakensberg basalt. In addition, thin section studies (Appendix A) showed basaltic grains in the sandy fraction of the basal conglomerates in the Mmashoro area that comprise calcrete clasts with a few agate, carnelian and basalt clasts. In the South Sua Pan Area (Fig. 3d, section 5.3.1) and parts of the Mmashoro Area (Fig. 3f, section 5.5.2) the Dikara Member is made up of underlying basalt, agate and subordinate pre-Kalahari calcrete clasts.

The matrix of all the basal conglomerates encountered in the study areas consists of calcreted, clay-rich sand.

In the areas where thick basal conglomerates were described by Mabbutt (1955) and Smit (1977), the local and regional geology was more conducive to the formation of resistant clasts during erosion. For example, the Nama sandstone, granite, gneiss, vein quartz and quartzite clasts in the west (Du Toit, 1954; Mabbutt, 1955) and resistant Dwyka tillite clasts in the Molopo area (Smit, 1977) of the south are much more resistant than the weathered Drakensberg basalts that underlie the Kalahari Group in the study areas. In addition, the more resistant agate clasts only make up a small percentage (less than 2 percent) of the Drakensberg basalt in the study areas. The result is that the basal conglomerates of the Kalahari Group in these areas have a limited thickness.

Possibly, the "Kalahari basin" should be divided into sub-basins, each with its own Early Kalahari stratigraphy. This would make direct correlation of the Kalahari Group in northern Botswana with areas as distant as Namibia (Mabbutt, 1955) and South Africa (Smit, 1977) difficult, if not impossible.

The model for the depositional environment of the majority of Kalahari Group sediments, fits the description of saline lake sediments, as given by Hardie et al. (1978).

Saline lakes are surrounded by a complex of genetically interrelated depositional sub-environments (Hardie et al., 1978). From a sedimentological point of view, the closed saline lake basin is usually considered as a whole, with the actual saline lake forming only one part of it (Fig. 7).

The basal conglomerates in the proximity of faults are interpreted as alluvial fan deposits. In saline lake basins, such as those of the Kalahari Group, that formed as a result of block faulting, alluvial fans often surround the saline lakes of the graben floors. The conglomerates found at the base of the Mmashoro Formation, further away from faults (see section 5.5.2) are considered to be the result of channel scour and fill. These fluvial conglomerates decrease gradually in thickness away from the proximal part (see section 5.5.2) of the basin to eventually disappear in the distal part (see section 5.5.3) of the basin.

### (3.1.1.2) Sandstone

Superficially, the characteristics of the Mmashoro sandstone appear remarkably similar in all four study areas. On closer inspection however, differences emerge. Sandstone of a fluvial (section 5.4.1), lacustrine (sections 5.2.1 and 5.5.3) and fluvio-lacustrine (5.5.2) nature can be recognized in outcrops.

Since deposition is considered to have taken the form of graben in-filling (section 5.3.1), there was a mixture of fluvial and lacustrine sand in grabens (Fig. 7). The sand was subsequently bioturbated moderately to extensively (Figs. 6, 23 and 24). The oxidation in some of the sandstone (Appendix 1) could have taken place both subaerially or under shallow lacustrine conditions. With drill chips from a borehole of which the position in the depositional basin is not known, it would be impossible to determine if the oxidized, bioturbated Kalahari Group sandstone is of a fluvial, fluvio-lacustrine or shallow lacustrine nature as they would all appear much the same.

The well known and descriptive term "Pipe Sandstone" of Maupe (1939) can be correlated with the Mmashoro Sandstone Formation in this thesis. The Mmashoro Sandstone Formation includes all the Early Kalahari sandstone, the basal conglomerates described above as well as the purely lacustrine rhythmites (see sections 3.3 and 5.2.1). In the study areas, Mmashoro sandstone without iron-oxides is considered to be deposited under water in purely lacustrine environments (section 5.5.3).

The Mmashoro Sandstone Formation was called "Grès Polymorphes" by Cahen and Lepersonne (1952), while Money (1972) termed it the "Lower Barotse Formation", although no distinction was made between sandstones with or without iron-oxides.

The term "Pipe Sandstone" is derived from the numerous pipe-like structures often seen in outcrops of the sandstone (Plates 20 and 21). These "pipes" are in fact trace fossils (mostly *Thalassinoides*) (see section 5.5.3) that have weathered negatively to form hollow tubes.

Diagenesis and weathering have highlighted the trace fossils. Thin section studies (Appendix 1) have shown that the in-filled trace fossils often have more carbonate cement than the surrounding sediment in fresh rock specimens (Plates 10, 27 and 31). Acid rainwater that percolates down the soil profile can leach out the carbonate in the trace fossils to form hollow tubes. The continued leaching of carbonate out of the sidewalls of the hollow trace fossils often produces "halos" around the trace fossil. In fresh rock specimens, backfilled trace fossils with U shaped backfilling ("spreiten") can sometimes be seen.

In some instances, such as in the silica-rich lacustrine sediments of the Mmashoro Area (Fig. 3f, section 5.5.3), the trace fossils contain more silica than the surrounding sediment and weather positively (Plate 24).

The spatially extensive bioturbated sandstone (oxidized and unoxidized) makes up the biggest volume of the Mmashoro Sandstone Formation and the Kalahari Group as a whole within the study areas and is therefore treated in some detail in the following discussion.

Basal conglomerates in close proximity to faults grade laterally into and are often overlain and scoured by oxidized sandstone (Figs. 15, 16, 17, 18 and 19). The sandstone occasionally contains reworked conglomerate clasts at the base. The sandstone in turn grades into and is overlain by well sorted, unoxidized lacustrine sandstone (see section 5.5.3).

Sandstone of the Mmashoro Sandstone Formation typically has the following characteristics:

#### Texture:

- (a) *Grain size:* The grain size ranges from fine to coarse.
- (b) *Grain shape:* Roundness: Rounded to subangular  
Sphericity: Ranges from prismoidal to discoidal.
- (c) *Sorting:* The sorting varies from moderately sorted in the fluvial facies to well sorted in the lacustrine facies.
- (d) *Fabric:* The packing is ordered.

#### Colour:

The colour varies from yellowish brown to dark reddish brown due to the presence of iron-oxides (Appendix 1) in some fresh rock specimens, while there is a distinct lack of iron oxides in the distal lacustrine sandstone. The lacustrine sandstone appear grey in colour.

#### Induration:

Hard, due to cementation by carbonate and silica.

### Degree of calcretization, silcretization and ferricretization:

The amount of silica and carbonate cement in the sandstone varies according to the position in the depositional basin. In the fluvial (section 5.5.4), fluvio-lacustrine and basal lacustrine sandstone (section 5.5.3), carbonate dominates over silica. Thin section studies on fresh rock specimens show continuous carbonate overgrowths on grains, with the remaining voids being filled in with silica (Plates 25 and 26). Towards the top of the lacustrine profile, under more saline conditions during the final in-fill and desiccation of the lake, silica becomes progressively more dominant until, in the topmost sandstone units, silica completely replaces carbonate in the matrix.

Occasionally, at or near the surface, iron oxides have replaced the carbonate and silica cement, as a result of subsequent wetter climatic conditions, to form ferricrete.

Many authors (Thomas and Shaw (1991) give an excellent summary of published work on the Kalahari Group) have preferred to look at the sandstones of the Kalahari Group simply as silcretes, rather than looking at the nature of the sediments prior to cementation. As will be shown in this study, sedimentary structures such as trough cross-bedding can be still be recognized, despite the silcretization. These and other sedimentary structures are critical for the understanding of the depositional environment and should not be ignored.

### Thickness:

The thickness of the Mmashoro Formation sandstone shows considerable lateral variation as it is dependent on the position of horst and graben structures (see section 5.3.1). As can be expected, the thickest successions of sandstone can be found in the deepest parts of the basins.

### Sedimentary structures:

(a) *Internal:* Trough cross-bedding dominates in the fluvial sandstone (section 5.4.1) and fluvio-lacustrine sandstone (section 5.5.2) with subordinate low angle cross-bedding, planar cross-bedding, ripple lamination and mud rip-up clasts. The fluvial sandstone also shows channels up to 4 metres wide, one metre deep and two metres apart (section 5.4.1). The lacustrine sandstone has massive or horizontal bedding (section 5.5.3).

The fluvial sandstones show some bioturbation in the form of vertical dwelling structures (Skolithos) and escape structures (see section 5.4.1). The fluvio-lacustrine sandstones show

moderate bioturbation in the form of irregular networks of tunnels and shafts of variable diameter (Thalassinoides) (section 5.5.2). The lacustrine sandstone shows very strong bioturbation in the form of Thalassinoides and ?*Lennea* (section 5.5.3).

(b) *On bedding surfaces:* The basal contact of the fluvial and fluvio-lacustrine sandstone shows scour-and-fill structures (sections 5.5.2 and 5.5.4).

Undisturbed surface openings of trace fossils (Figs. 22 and 23) were only preserved on the bedding planes of the lacustrine sandstone (section 5.5.3) under circumstances of intermittent slow deposition, but no erosion. In the fluvial sandstone where the bedding is characterized by erosional upper and lower contacts, the top of the bed is recognized by erosional truncations of distinct burrows (section 5.4.1). The fluvio-lacustrine sandstone displays "post-erosion" Thalassinoides burrows that cross-cut erosional planes due to the subsequent bioturbation of sand laid down initially by fluvial processes in a dominantly shallow lacustrine environment (section 5.5.2).

#### Palaeocurrents:

Palaeocurrent directions can often be obtained from the fluvial and fluvio-lacustrine sandstone by measuring the axes of trough cross-bedded sets in plan view (section 5.5.2).

#### Interpretation:

Sandstone, interpreted as fluvial (section 5.4.1), fluvio-lacustrine (section 5.5.2) and lacustrine (section 5.5.3) in nature, has been recognized in the Kalahari Group of the study areas. All these sandstones are interpreted as having progressively filled in block-faulted grabens. In the proximal part of the depositional basins, conglomerates grade laterally into fluvial sandstone, which in turn, grades laterally into lacustrine sandstone in the distal part of the basin. The sandstone also grades upwards into lacustrine sediments that consist of rhythmites (sections 3.3 and 5.2.1) and which represent the final desiccation of the saline lake environment.

Since the sandstone comprises the largest volume and is the most commonly found consolidated sediment of the Kalahari Group, the Mmashoro Sandstone Formation is considered the most suitable term to describe the Early Kalahari sediments of the study areas. Once a worker has found consolidated Mmashoro Formation sandstone in outcrops or boreholes, he only has to classify it as fluvial, fluvio-lacustrine or lacustrine; try to obtain palaeocurrent directions, and then look upstream for conglomerates and downstream for lacustrine sediments in order to find his relative position within the depositional basin.



### (3.1.1.3) Rhythmites

Rhythmites form part of the lacustrine facies of the Mmashoro Formation and have a large spatial extent in the study areas. Rhythmites in Early Kalahari sediments have been recognized in the Orapa-Letlhakane Area (see section 5.2.1) (Plates 3 and 4) and Mmashoro Area (see section 5.5.3). Younger rhythmites which form part of the Makgadikgadi lake sediments were found in pans in the Orapa-Letlhakane Area (Fig. 3c), South Sua Pan Area (Fig. 3d) and Nata Area (Fig. 3e). These younger rhythmites are, in contrast to the cemented Mmashoro Formation rhythmites, unconsolidated and can be trenched with a spade. A similar depositional environment must have prevailed in Early Kalahari times to that found in the Makgadikgadi pans today.

Rhythmites are thought to have formed in ephemeral saline lake environments in the following way:

In an ephemeral saline lake, deposition of clastic sediment takes place as sand, silt and clay settle out of suspension when the turbulence of flood waters subsides. This leaves a lamina or thin bed of sandy mud on the lake bottom.

With continued evaporation, and the abundance of silica (from clay minerals?) in the Kalahari environment, the pH of the lake water rose sufficiently for silica to go into solution. Continued evaporation caused the silica, firstly to be precipitated as a gel and secondly to develop desiccation cracks on the top surface of the silica-gel (chert). A single flood would result in the deposition of a couplet comprising a thin sandy mud layer and a (normally thicker) chert layer. Repeated floods superimposed the couplets to form lacustrine facies that locally exceed five metres in thickness (Plates 3, 4 and 5, Locality A, Orapa-Letlhakane Area (Fig. 3c)).

Rhythmite deposits with thicknesses exceeding 5 metres have been recognized in the study areas and typically consist of layered black, grey or yellow chert and fine-grained green sandstone in fresh rock specimens (Plates 3 and 4). In the Mmashoro Area, the lacustrine sandstone described above, grades laterally into and is overlain by rhythmites (section 5.5.3).

Individual chert and sandstone layers vary in thickness from less than 1 mm to 30 mm. Desiccation cracks (Plate 5) (sometimes filled with oxidized terrestrial sand) found in Mmashoro Formation rhythmite deposits indicate sub-aerial exposure. Small-scale tepee-structures (Plate 4), formed by repeated cycles of desiccation and thermal contraction, coupled with thermal expansion and hydration (section 5.2.1), are common in the rhythmites. Tepee-structures are indicative of sub-aerial exposure, a semi-arid climate and periods of reduced sedimentation or non-deposition.



The rhythmites represent the final stages of graben in-filling during which evaporation exceeded inflow under semi-arid climatic conditions (see section 5.2.1). Ephemeral saline lake conditions as described by Hardie et al. (1978) prevailed.

Saline lakes normally contain water with more than 5000 ppm of dissolved solutes, the upper salinity tolerance of most freshwater organisms (Hardie et al., 1978). Water salinity in the Kalahari lakes must have been sufficiently high to precipitate glauconite (section 5.2.1) and to allow stromatolites (section 5.5.3) to form. Biogenic traces, with the exception of the small, dome-shaped stromatolites in the Mmashoro Area (section 5.5.3) are therefore absent from the rhythmite deposits.

### (3.2) MAKOKA SUBGROUP:

#### (3.2.1) The Letlhakane Stoneline Formation (LSF)

The final in-filling and desiccation of the block-faulted grabens described above, was followed by what is interpreted as a long period of non-deposition, weathering and erosion in the Tertiary that lowered the landscape by more than 25 metres in the Orapa-Letlhakane Area (see section 5.2.3). This lowering of the landscape produced a spatially extensive pebble lag that is called the Letlhakane Stoneline Formation (abbreviated to LSF). Wells et al. (1990) give a brief summary on work done on stonelines and describe stonelines in Madagascar that are buried lag gravels outlining former hill and valley surfaces. They concluded that stonelines are polygenetic.

The LSF was found in outcrops and borrow-pits in all four study areas in northern Botswana (Fig. 2) and makes up the basal unit of the Makoba Subgroup. The LSF was also recognized in borehole chips and makes an excellent marker horizon separating the hard, consolidated, Orapa Subgroup deposits from the younger, generally soft, Makoba Subgroup deposits (Fig.6).

The LSF also occurs far beyond the borders of the study areas in northern Botswana. Conglomerates that fit the description and stratigraphic position of the LSF, were reported by Passarge (1904) as "Basal river gravels" at the base of the "Kalahari Sand", while Maufe (1939) termed it the "Carstone nodule bed".

The thickness of the LSF varies from 3 cm to about 200 cm in the study areas. Due to the denudation of the landscape which produced the LSF, the conglomerate consists of resistant clasts from the underlying (or formerly underlying) bedrock. In most cases, the clasts comprise the more resistant elements of the Early Kalahari age Mmashoro Sandstone Formation. The LSF can be unconsolidated (Plate 12), calcreted (Plates 7 and 13) or ferricreted (Plates 7 and 11).

#### (3.2.2) Debe Calcrete Formation

Spatially extensive calcretes, up to 1 metre thick, occupy a specific stratigraphic position in that they overlie and inundate the LSF in all four study areas. The calcretes, called the Debe Formation after a village in the Orapa-Letlhakane Area, are in turn overlain by the unconsolidated Gordonia Formation (see section 3.7) (Plates 7, 8, 12, 14 and 15). The calcretes have a displacing effect on the LSF clasts (Plate 13). In many localities, subsequent wetter climatic conditions have caused calcretes to dissolve and a karst

surface to develop (Plates 14 and 15). The removal of the displacive calcrete caused the LSF to return to its original clast-supported state (Plate 12) or to become ferricreted (Plate 11).

The Debe Formation calcretes that cover the LSF are mostly hardpan (as described by Goudie, 1983) with a cap of laminar calcrete that has a maximum observed thickness of 10 cm. Minor nodular and honeycomb calcrete also occurs. Classification, however is hampered by calcretes that form composite profiles in the study areas.

The normal problems with stratigraphic correlation on the margins of basins are encountered with the calcretes and Late Kalahari sediments in general. To the south west of the study areas in the Central Kalahari, the Makoba Subgroup sediments attain a much greater thickness of up to 50 m, compared to a maximum thickness of only 5 m in the study areas. In the Central Kalahari basin (to be discussed in detail in the author's PhD thesis) regional calcretes are separated by sand layers. In the present study areas, close to the margins of the Kalahari basin as a whole, the calcretes have coalesced to form a compressed sequence. Most of the work has been conducted so far on the margins of the Kalahari basin (e.g. Mabbutt, 1955 (southwestern margin) and Maupe, 1939 (northeastern margin)) where the superimposition of different calcrete profiles has defied stratigraphic correlation. The above-mentioned problems make correlation of different calcretes in the present study areas impossible and the calcretes are therefore treated as a single formation in the Makoba Subgroup which post-dates the formation of the LSF and is overlain by the unconsolidated Gordonia Formation (section 3.1.7).

### (3.2.3) Ferricretes

Ferricretes are found in the LSF where iron oxides have replaced the calcrete in the matrix under subsequent wetter climatic conditions. The ferricrete now cements the LSF clasts in many localities in northern Botswana. Some Middle Stone Age artefacts were cemented by the ferricrete in the South Sua Pan Area (Fig. 3c). This gives an indication of the relatively young age of at least some of the ferricretes.

### (3.2.4) The Gordonia Formation

Due to its surface expression and large spatial extent, most studies on the Kalahari Group have concentrated on the Gordonia Formation (SACS, 1980). The term "Gordonia Formation" is used here only for the unconsolidated, uppermost member of the Kalahari Group and does not include any calcrete. Aeolian

sedimentary characteristics dominate the Gordonia Formation (Flint and Bond, 1968; Binda and Hildred, 1973; Lancaster, 1986a and Thomas, 1988). Outliers of the Gordonia Formation (and in fact the whole Makoba Subgroup) lie far beyond the present limits of Early Kalahari outcrop or sub-crop (Figs. 1, 2 and 3).

Linear dunes (Thomas and Shaw, 1991) of the Gordonia Formation (SACS, 1980) can be recognized in the Mmashoro Area (Fig. 3f) (see section 5.5.5). These dunes are low features, generally less than 3 metres higher than the interdune areas. The Gordonia Formation has a maximum observed thickness of 4 metres in the study areas. The linear dunes have undergone degradation and are thought to be remnants of what were formerly much larger dunes. The dunes are vegetated by trees, shrubs and grass and show no internal bedding due to bioturbation.

On average, the Gordonia Formation contains over 90 % quartz, with most of the sand grains between 2 mm and 0.063 mm in diameter (Thomas and Shaw, 1991) and has a dark red to pale brown colour due to iron oxide coatings on grains. Near the surface, the sand is often bleached grey to white, especially in the interdune areas where water collects seasonally.

Thomas and Shaw (1991) give a summary of work done on the Gordonia Formation and conclude that the bulk of sand was derived locally from in situ weathering of underlying lithologies with some input along fluvial and aeolian pathways.

The age of the Gordonia Formation is considered to be Holocene. A thermoluminescence (TL) date at the base of the aeolian Gordonia Formation at Jwaneng Mine (Fig. 1) was given as 11 000 BP (Halliwell, 1987). J. Ward (pers. comm., 1992) reports an age of 6000 BP for dunes of the Gordonia Formation in the Windhoek Graben (Namibia). Absolute dates for dunes of the Gordonia Formation in the literature are also of Holocene age, e.g. Rust (1984) gives an age of 3510 BP from calcrete taken within a dune field in Etosha (Namibia), while Lancaster (1986b) gave a minimum age of 1000 BP for the formation of a dune in the southwestern Kalahari.

### (3.3) Makgadikgadi Subgroup:

Sediments of the Makgadikgadi Subgroup (which will not be covered in any detail in this thesis) consist of minor conglomerates, abundant sandstone, siltstone and mudstone, diatomaceous deposits and rhythmites.

Glaucinite is only found at and near the top of the lacustrine facies of the Mmashoro Sandstone Formation, where the water conditions must have been neither too acidic nor alkaline (see section 5.2.1) and similar to a marine environment. In the Makgadikgadi lake sediments however, glauconite (see section 5.3.1) is very common (PdP/JPLR/Mos/LS, Appendix 1) (Plate 35). The green colouring in the lake sediments (Plates 9 and 35) has also been recognized as glauconite-illite by Summerfield (1982). The glauconite therefore gives some insight into the lake water conditions.

It should also be noted that similar lacustrine conditions prevailed during deposition of some of the Mmashoro Sandstone as well as of the Makgadikgadi lakes e.g. the conditions that led to the formation of rhythmites. These Recent rhythmites could be trenched with a spade and was also found in pans by Coates et al. (1979) in the Orapa area. For this reason, the classification of sediments, taken out of their stratigraphical context, can be difficult and misleading (Mmashoro Sandstone rhythmites and consolidated Makgadikgadi rhythmites would appear the same since the depositional environment was similar).

#### (4) BIOTURBATION OF THE KALAHARI GROUP SEDIMENTS

Sediments of the Kalahari Group have often been extensively bioturbated, making recognition of primary sedimentary structures difficult, if not impossible. As discussed in section 3, the Mmashoro Sandstone Formation contains numerous trace fossils. Processes such as solution, leaching and mineralization, that often destroy or modify body fossils such as shells, bone and wood, very often enhance the preservation of trace fossils (Frey, 1975). As mentioned in section 3.2, diagenesis and weathering often highlight trace fossils in the Mmashoro Sandstone Formation. Numerous silicified *Thalassinoides* trace fossils have also been found in the study areas. Trace fossils play an important role in the later stages of diagenesis due to the different porosity, pH, Eh, and organic content of the burrow-fill and adjacent sediment (Frey, 1975). Trace fossils may therefore act as foci for cementation and replacement. A whole range from partly silicified burrow fills to perfect burrow pseudomorphs can be found in the Mmashoro Sandstone.

Trace fossils can make a substantial contribution to the understanding of Kalahari Group palaeoecology, sedimentology and facies analysis. For example, the trace fossils in the Mmashoro Area at A1 (Fig. 3c) (section 5.5.2) aided in the recognition of the sediments as fluvio-lacustrine. At this locality the trough cross-bedded sediments imply moderate to high energy conditions and rapidly transported sediments, a combination that is unfavourable for most trace makers (Frey, 1975). The prolific trace fossils cross-cutting trough cross-bedded sets, especially in the upper part of the succession, indicate that local energy conditions diminished before bioturbation took place on a large scale.

The trace fossils at A1 in the Mmashoro Area were identified as *Thalassinoides*. This is interesting as *Thalassinoides* is usually confined to the marine environment (Frey, 1975). However, near-marine and marine salinity were attained in the Early Kalahari saline lakes as can be seen by the presence of glauconite (section 5.2.1) and stromatolites (section 5.5.3). "Typical" marine trace fossils such as *Thalassinoides* can therefore also be found in the lacustrine and fluvio-lacustrine sediments of the Kalahari Group.

At A1 (Mmashoro Area) the majority of the sediments accumulated initially in a fluvial environment. The *Thalassinoides* trace fossils were formed at a later stage when marine-like waters covered the unconsolidated sediments.

In the Nata Area (Fig. 3e) (section 5.4.1) however, trace making occurred contemporaneously or penecontemporaneously with sedimentation, since the laminae truncate most of the traces, while some traces represent escape structures.



The reason for diagenetic preservation of trace fossils can be seen in thin sections (Plate 10, 27 and 31) (Appendix 1), where the trace fossils contain much more carbonate than the surrounding sediment. The presence of more carbonate in some burrows may be due to the increased porosity of the burrows compared with that of the matrix, and consequent control over the migration of pore fluids.

The oxidized trace fossils in an unoxidized matrix, seen in the Mmashoro Area at C (section 5.5.4) may be due to the respiratory or water-pumping activity of burrowing animals. Alternatively, water and sediments from shallow, oxidizing lacustrine conditions that followed the deposition of deeper water sediments, could have percolated down burrows.

The well preserved, sharp edges of burrows in the Mmashoro Sandstone indicate bioturbation of the sediments while they were still wet and/or the mucus lining of burrows by organisms; otherwise the burrows would have collapsed behind them.

The organisms that bioturbated the lacustrine Kalahari Group sediments must have been able to withstand current and wave action, desiccation and rapid fluctuations in temperature and salinity. Organisms that can survive such conditions do so by escaping from the surface into semi-permanent burrows that are often lined with mucus to prevent collapse (Frey, 1975).

This organism response to extreme conditions is reflected in the corresponding trace fossils such as the three dimensional *Thalassinoides* burrows in the Kalahari Group. In the fluvial Kalahari sediments, where conditions were even harsher, a preponderance of vertical burrows, such as *Tigillites* (see section 5.4.1) is shown.

Examples of organisms that can tolerate the high salinity and/or alkalinity in saline lakes are fishes such as the *Tilapia* species, brine shrimps and other decapods, rotifers, copepods, nematodes, insect larvae, worms, some gastropods, blue-green algae and some halophyte plants (Hardie et al., 1978).

Trace fossils are also useful in that they give an indication of the compaction that sediments have undergone. Sediment-filled *Thalassinoides* burrows in the lacustrine sediments at B1 and B2 in the Mmashoro area (section 5.5.3) that are parallel or oblique to the horizontal bedding, underwent changes in shape. In cross section they are elliptical in form, while the burrows that are oriented perpendicular to the bedding remained cylindrical.

As mentioned previously, differences in the type and degree of bioturbation in the Kalahari sediments can be useful to the geologist. In the moderate to high energy fluvial sediments at C in the Mmashoro Area (section 5.5.4) and at A in the Nata Area (section 5.4.1) the bioturbation was not extensive and

organisms merely disturbed the pre-existing fabric. The foreset laminae of trough cross-bedded sets can still be recognized at these localities. In the low energy lacustrine sediments at B1 and B2 in the Mmashoro Area, organisms burrowing in the substrate completely obliterated the pre-existing fabric in some places. The trace fossils in the Kalahari Group are therefore important as they can be used as indicators of facies changes, which in turn indicates a change in the depositional environment.



## (5) STUDY AREAS:

### (5.1) Introduction

The maps of the Orapa-Letlhakane Area (Fig. 3c), South Sua Pan Area (Fig. 3d), Nata Area (Fig. 3e) and Mmashoro Area (Fig. 3f) are in part sub-crop maps, since the LSF and Gordonina Formation overlie older rocks down to the 920 m.a.s.l. strandline (beach ridge) (see Study Areas 1 and 3) and the Gordonina Formation overlies lake sediments down to the present day pans. In the South Sua Pan Area and the Mmashoro Area, the scarp forms the northern edge of the Naledi Subgroup distribution *per se*. In the maps, however, the distribution of the Naledi Subgroup is not shown for the sake of simplicity.

In the Orapa-Letlhakane Area, South Sua Pan Area and Nata Area, the tectonic control on the present distribution of the different lithologies can be clearly seen in the form of a fault that limits the eastern distribution of the lake sediments.

A great number of the faults have post-Karoo dolerite dykes associated with them, which utilized these weak zones in the crust. Tectonism is still active in the region, since the area around the Makgadikgadi Pan Complex is, in part, an extension of the East-African Rift system (Reeves, 1972; Reeves and Hutchings, 1975; Du Plessis, 1990). A large number of faults must have been re-activated several times in the Cainozoic. The block-faulting caused considerable erosion from the up-thrown blocks in the area during the post-Karoo to Recent period. Blocks with subcrops of the Mosolotsane Formation indicate erosion of at least 100 metres, if both the Drakensberg Basalt and the Ntane Formation are presumed to have overlain the Mosolotsane in these blocks.

The fault-controlled northern limit of the Drakensberg basalt, as well as the course of the Letlhakane River, can be seen on the Orapa-Letlhakane Area map.

Fluvial transport in the Holocene and probably earlier, was towards the north and northwest in the Orapa-Letlhakane Area, as can be seen by the number of streams (many of them now dry all year round) draining into the former and present Makgadikgadi lakes.

The Makoba Subgroup dunes in the study areas have WSW trends, produced by prevailing winds from the ENE.

Transport was determined with the aid of trenches to have been both parallel and perpendicular to the major NW trending faults in the major Early Kalahari graben at F in the South Sua Pan Area (Fig. 15) (section 5.3.1).

## (5.2) Orapa-Letlhakane Area (Fig. 3c)

### (5.2.1) Profiles A, B, C and D (Orapa-Letlhakane Area)

In profile A (Fig. 8), consolidated green and grey rhythmites overlies reddish brown, bioturbated sandstone. These are interpreted as Early Kalahari sediments of the Orapa Subgroup as they overlie Drakensberg basalt and are in turn overlain by the Letlhakane Stoneline and Gordonian Formation in the vicinity of profile A. Unfortunately, the contact between the rhythmites and brown sandstone is obscured by rubble. The Mmashoro sediments at A are interpreted as lacustrine facies.

#### Reddish brown lake sediments

The pale reddish brown sandstone in the vicinity of A (Orapa-Letlhakane Area) is fine- to medium-grained and moderately to poorly sorted (Samples PdP/BK/L1, PdP/BK/L2 and PdP/BK/L3, Appendix 1). More than 80 percent of the medium to coarse grains are rounded to sub-rounded, with about 60 percent of the smaller sand grains sub-angular to angular. The principal minerals are quartz (85%) and carbonate-rich mud (11%). Carbonate cement in the form of micrite, heavy minerals, iron oxides and silica cement in the form of chalcedony (Plates 25 and 26) make up the remaining 4 percent (Appendix 1).

The sandstone shows evidence of moderate bioturbation (Thalassinoides trace fossils) and generally has a massive structure as a result. The 3-D network of burrows that are 1 to 3 cm in diameter, typically show Y-shaped branching patterns. Near the weathered surface of the outcrop, the trace fossils are hollow tubes. In fresh rock specimens the burrows are filled with sand and carbonate. Concavo-convex "spreiten" (backfills) have been recognized in some of the burrows.

The iron-oxide coatings on grains (Appendix 1) indicate sub-aerial exposure or shallow water conditions during sedimentation. The absence of iron-oxides in the back-filled Thalassinoides burrows indicates that bioturbation took place under deeper water conditions (Plate 27). Thalassinoides trace fossils are typical of low-energy regimes, normally in a marine environment, below wave base (Frey, 1975). The trace fossils in these oxidized sediments at A therefore are strongly indicative of sedimentation and bioturbation in a lacustrine environment.

On macroscopic as well as microscopic scale, the sharp edges of burrows, supporting the interpretation of bioturbation during a wet period and/or the mucus lining of burrow walls for support, can clearly be seen. An interesting observation is that the burrows contain much more heavy minerals, especially zircon (4%), than the surrounding sediment (0.5% zircon). This may be

the result of the biogenic downward transport of overlying sediments with a different heavy mineral composition, to the reddish brown, oxidized, bioturbated sandstone. Alternatively, sand with a different heavy mineral assemblage could simply have washed into the open burrows.

The calcium carbonate cement (micrite) in the sediment is considered to be a diagenetic feature, chemically precipitated from the groundwater. The carbonate cement forms continuous overgrowths on some of the grains.

The burrows contain substantially more micritic carbonate (14.9%) than the surrounding sediment (0.1%) in sample PdP/BK/L3 (Appendix 1). The abundant calcium carbonate in the burrows may either be the result of the downward percolation of the overlying calcium carbonate-rich water at the time of bioturbation or due to easier movement of carbonate-rich groundwater through the burrows during diagenesis.

The oxidized, brown, shallow lacustrine sandstone at A grades eastwards into oxidized fluvial sandstone with no trace fossils and large desiccation cracks (with saline mineral growth in the cracks) one kilometre east of B (Plate 6).

#### Green lake sediments

The rhythmites that overlie the oxidized, shallow lacustrine sandstone at A, lie at a much higher elevation than the younger and softer Makgadikgadi Subgroup rhythmites further north in pans in the Orapa-Letlhakane Area. This is probably due to tectonic uplift of these older consolidated Early Kalahari lacustrine sediments. As can be seen from Fig. 3c, numerous faults transect the area. Remnants of Mmashoro Formation lake sediments have also been found at hills B, C and D, as well as on the Orapa Township hill - representing reverse topography. At A, D and the Orapa Township, the lake sediments consist entirely of green and black rhythmites (Plates 3, 4 and 5), while the successions at B and C only contain rhythmites in their upper parts - the rest being massive, green, intensely bioturbated sandstone.

Thalassinoides trace fossils from 0.5 to 3 cm in diameter are abundant in the green sandstone at B and C.

The pale green sandstone at B and C is moderately to well sorted, varying from fine- to coarse-grained. The medium to coarse grains form only a small part (about 10%) of the sandstone and they are invariably well rounded to sub-rounded. About 60% of the smaller sand grains are sub-angular to angular. The majority of the grains in the green sandstone have therefore not been transported very far. This is to be expected from a low energy lacustrine environment.

The green colour is due to green glauconite-rich clay in the matrix. The presence of glauconite indicates deposition under saline water in a slightly reducing environment.

Also significant is the difference between the grain sizes, roundness and sorting in the backfilled burrows and the sandstone at C (Plate 31) (Samples PdP/L/H1 and PdP/L/H2, Appendix 1). The grains in the burrows at C also show orientation parallel to the long edges of the oval cut through the burrow that can be seen in thin section PdP/L/H1 (Appendix 1). The immature nature and orientation of the sediment in the burrows can either be the result of:

- (1) the biogenic transport of immature sediment from above or below the sandstone bed and the backfilling action of the organism or,
- (2) the oriented backfill represents excrement from the bioturbating organism that fed exclusively on the fine sand and clay fractions.

The calcium carbonate, in the form of sparite, forms continuous overgrowths, with crystal growth perpendicular to the grain surfaces. The carbonate replaces the clay minerals in part. The remaining voids are filled in by silica in the form of chalcedony. The calcium carbonate and chalcedony are considered to be diagenetic features.

The basaltic rock fragments and plagioclase in the sandstone at C indicate that it was at least partly derived from the underlying Karoo basalt.

The green sandstone at B and C is interpreted as saline lacustrine sediments that were deposited in deeper water, where conditions were slightly reducing, while the oxidized, reddish brown lake sediments represent deposition in shallow water.

## Rhythmites

Tectonism and climate were probably the major controls on Kalahari saline lake sedimentation. Tectonism shaped the horsts and grabens, whereas the climate controlled the amount of precipitation and evaporation, the nature of weathering, the nature of the soil in the catchment areas, the vegetation, as well as the volume of sediment brought into the basins.

In saline lakes, especially in arid and semi-arid environments, the pH is very high (Hardie et al., 1978) which causes silica (provided by clay minerals) to go into solution. When the pH drops due to continued evaporation, CO<sub>2</sub> loss, influx of acid rainwater, etc., the silica precipitates in the form of chert or opaline silica gel (Watson, 1989).

The lake sediments in profile A (Orapa-Letlhakane Area) consist of horizontally layered black, grey or yellow chert and fine-grained, green, laminated sandstone (Plates 3 and 4). Individual sandstone and chert layers, which vary from less than 1 mm to 30 mm in thickness, are usually horizontal or slightly inclined because of deposition on originally inclined surfaces or compaction towards the center of the lake. Individual layers can be traced laterally for tens of metres - a strong indication for deposition under calm water conditions.

Thin section studies indicate that the green sandstone layers have normal grading and moderate to good sorting. The green colour is due to the presence of glauconite. In thicker sandstone layers the amount of glauconite-rich clay increases from the base to the top, and the texture varies from grain-supported near the erosional lower contact to matrix-supported. Near the top grains float in a horizontally-layered matrix of glauconite-rich clay (Plates 28, 29 and 30) (Sample PdP/L/L4, Appendix 1). This fining-upward sequence for each sandstone layer represents waning energy conditions. The green sandstone layers are also interpreted to have been deposited in current velocities unable to generate ripples, i.e. very calm, shallow water conditions as would be expected in a shallow lake.

With continued desiccation of the lake, the water became more alkaline, silica went into solution and, with further desiccation, precipitated again in the form of chert and opaline silica. The sandstone and overlying chert layers are therefore genetically related to form couplets.

After precipitation of the chert layer, desiccation continued until the eventual sub-aerial exposure of the sediments. This continued desiccation can be seen from the following:

- (a) The chert layers show well developed desiccation cracks of several orders (Plate 5).
- (b) Some deeper desiccation cracks have been filled by red oxidized terrestrial sand.
- (c) Petrographic studies show red iron oxide coatings on the sides of the desiccation cracks, as well as on the top surfaces of the chert layers (Sample PdP/L/L4, Appendix 1).
- (d) The chert layers often form small-scale tepee structures.

Abundant small tepee structures (Plates 3 and 4) were recognized in the rhythmites at A (Orapa-Letlhakane Area).

Tepee structures describe features which look like cross-sections of American Indian tents. They are common in many carbonate platforms and modern examples are forming in peritidal zones (Riccardo and Christopher, 1977).

At A, the tepee structures appear as more or less equally spaced compressional buckles in cross-section, distorting one or more layers of the rock (Plates 3 and 4). In plan view, the tepees form an irregular polygonal pattern. The sediment found within the fractures and related breccias of the tepees, is made up of allochemical silica and terrigenous sand grains, derived penecontemporaneously from the adjacent environments.

Tepees form during low stand periods of the ocean (or, in this case, a saline lake). Repeated cycles of desiccation and thermal contraction, coupled with cementation, hydration and thermal expansion cause tepee structures to form (Riccardo and Christopher, 1977). Tepee structures in the chert layers are interpreted to have developed as a result of the initial desiccation and subsequent wetting of each chert layer in the lake.

Tepee structures provide evidence for:

- (a) sub-aerial exposure,
- (b) arid to semi-arid climates and
- (c) periods of reduced sedimentation or non-deposition.

The length of exposure of each chert layer appears to have been fairly short because the tepee structures in the outcrop at A are small and simple. The complexity and, to a lesser extent, the size of tepee structures increase with the length of sub-aerial exposure (Riccardo and Christopher, 1977). The size of



tepee structures is dependent not only on time, but to a larger extent on the thickness, which is small in this case with the maximum thickness of laminae only 30 mm.

These features described above in the rhythmites indicate sub-aerial exposure, and also confirm the ephemeral nature of the saline lake in these parts and the semi-arid climate at the time. This type of rhythmic bedding can also be seen in the present-day pans to the north of Orapa, where the recent, soft sediments can be cut with a spade. This may indicate climatic conditions for the Letlhakane deposit very similar to the semi-arid climate of today.

The rhythmites in the lake sediments of the Letlhakane village outcrop at A, are therefore interpreted to be the result of fluctuations in the sediment load, the amount of water available and the evaporation rate. The green sandstone layers represent periods of fresh influx of water and sediment into the lake under (usually) low energy conditions. The chert layers formed with continued desiccation of the lake until eventually, the sediments became sub-aerially exposed.

At the top of the ephemeral saline lake sequence at A, there is a matrix-supported conglomeratic breccia with a maximum thickness of 30 cm. This bed consists of angular fragments of previously layered chert supported by a matrix of silica.

The former top surfaces of the chert in the breccia can be recognized from the desiccation cracks in thin sections (PdP/L/L5, Appendix 1). Iron-oxide rich calcium carbonate, that forms thin, but continuous overgrowths on grains and clasts, as well as part of the matrix, indicates sub-aerial exposure during or immediately after deposition, or at least shallow water conditions. Silica in the form of chalcedony filled in the remaining voids and shows perpendicular growth from the carbonate-coated grain and clast surfaces.

With desiccation and redeposition of silica in cracks, followed by expansion during wet periods, breccias can develop from tepee structures. Alternatively, this could also be a storm breccia that formed due to wave action that broke up the semi-consolidated chert layers.

The abundant presence of glauconite in the lake sediments at A, B, C and D, sheds some light on chemical aspects of the lake water. Glauconite is mainly restricted to marine continental shelf sediments, where there is some turbulence, some organic matter and low rates of sedimentation (Reineck and Singh, 1980). Glauconite also requires Eh-conditions that are not too oxidizing or reducing. Conditions in the Kalahari lakes may have been similar. In semi-arid environments, saline lakes can easily attain briny compositions similar to the marine environment (Hardie et al., 1978).

Evidence for bioturbation is absent in the layered chert deposits at A (Orapa-Letlhakane Area). This indicates that these briny, alkaline waters were hostile to the organisms normally found in saline lakes. These organisms would include worms, gastropods, crustaceans, decapods, etc. (Hardie et al., 1978). Evidence for bioturbation (Thalassiniodes trace fossils) in the Mmashoro lake sediments is, however, common further north at B and C - indicating less saline, deeper water conditions.

Only towards the top of the successions at B and C, were conditions saline enough to prevent bioturbation and cause the chemical precipitation of layered chert. At C and D, the green, fine- to medium grained, lacustrine sandstone directly overlies Drakensberg basalt. The absence of oxidized sediments here indicates deeper water conditions. The Mmashoro Formation sediments in the vicinity of Orapa and Letlhakane are therefore interpreted to be low energy, shallow lacustrine sediments deposited under semi-arid climatic conditions. The rhythmites represent the final in-filling of the lake, in which bioturbation had come to a halt due to hyper-saline conditions.

#### (5.2.2) Letlhakane Stoneline Formation at the Letlhakane Mine

The Letlhakane Stoneline Formation (LSF) overlies Drakensberg basalt and brown, oxidized, moderately bioturbated sandstone of the Mmashoro Sandstone Formation (Orapa Subgroup) in this profile, which is considered a type section for the Letlhakane Stoneline Formation. In other localities in northern Botswana however, the LSF also overlies Archaean basement and Karoo rocks as well as post-Karoo dolerites and kimberlites. The LSF has a very large aerial extent, from the northern Orange Free State in South Africa to the central part of Zaire (C. Skinner, pers. comm., 1990). It also occurs in the western part of Zimbabwe and the eastern part of Namibia. The LSF is always developed underneath the Gordonia Formation (Fig. 6) and is therefore an excellent marker horizon. The thickness of the LSF varies from a few centimetres to a maximum of three metres. The LSF can be unconsolidated, calcreted or ferricreted.

The LSF in the Letlhakane Mine profile is clast-supported and poorly sorted with an inverse-normal grading. However, in most other exposures of the LSF there is an absence of grading or stratification. It is normally overlain by the unconsolidated sands of the Gordonia Formation, but in places where the sand cover has been removed by erosion, the LSF outcrops as a gravel horizon. The sub-angular to sub-rounded clasts are ferricreted in the top third of the LSF profile, whereas the lower two thirds is calcreted (Plates 7 and 8). A karst surface developed on this calcreted part is related to a wetter climate during which the calcrete dissolved and ferricretes developed.



The lateral variation in thickness, the average size of the ten largest clasts and also the clast composition (Fig. 9) were measured east of 2125 D/K 1 (Fig. 12). The lower contact of the LSF undulates (Fig. 9), but shows a general eastward decrease in height above sea-level away from the kimberlite, identifying a palaeo-high represented by the latter during the formation of the LSF.

The clast composition consists almost entirely of:

- (a) fine- to medium-grained, brown sandstone clasts that contain *Thalassinoides* trace fossils and are similar in description to the oxidized sandstone at A - derived from the Mmashoro Sandstone Formation (Orapa Subgroup),
- (b) clasts such as weathered basalt, agate, carnelian and quartz - derived from the Drakensberg basalt.

In a few places around kimberlites 2125 D/K1 and D/K2, remnants of unoxidized lake sediments (green, fine-grained sandstone, chert and silicified *Thalassinoides* burrow fill) were found. This indicates that thin layers of the saline lake sediments covered 2125 D/K1 and D/K2 at some stage and have since been destroyed by weathering and erosion.

Clasts derived from the Mmashoro Sandstone Formation dominate the thickest part of the LSF, while clasts from the Drakensberg basalt are more prominent on the thinner, elevated parts (Fig. 9).

The LSF around 2125 D/K1 and D/K2 is interpreted to be in part a scree-flow deposit, as indicated by the following:

- (a) The average size of the ten largest clasts in the LSF, compared to the corresponding thickness of the LSF, plots more or less on a straight line ( $y = 2.3815 + 0.0181x$ ) (Table 1, Fig. 10). The regression coefficient ( $R = 0.59$ ) is significant at the 0.02 significance level.

This means that there is indeed a correlation between the mean pebble size (MPS) and the bed thickness (BTh) of the Letlhakane Stoneline Formation. Only gravity flow deposits will plot on a straight line, other fluvial type deposits will give a random scatter on this type of graph (Nemec and Steel, 1984). Fig. 10 also suggests that the deposition of the LSF took place here under wet conditions, with plastic flow (cohesion-strength-factor of 2.3815).

- (b) The LSF has an inverse-normal grading in the measured profile, fairly typical of gravity-flow deposits (Fisher, 1971).

- (c) A composite map (after the method by Le Roux and Rust, 1989) (Figs. 11, 12 and 13) of the volume of the LSF around 2125 D/K1 and D/K2 and the concentration of heavy minerals derived from the kimberlite pipes, shows distinct radial

transport directions in the LSF, off the palaeo-highs of D/K1 and D/K2. The weights assigned to the volume of LSF and concentration of heavy minerals that were used to produce the composite map are confidential.

Calculations (confidential) showed that the period of non-deposition that produced the LSF in this area, caused the landscape to be lowered by a minimum of 25 metres and a maximum of 50 metres during that time. The LSF is therefore considered to have originated as a residual lag deposit.

Evidence for gravity flow seen in this deposit is considered to be restricted to the slopes of palaeo-highs. The gravity flow therefore took place after the formation of the lag, probably during a wet period. In most outcrops of the LSF, no evidence for transport has been found.

Artifacts of the Middle and Late Stone Ages, have been found either at or very near the top of the LSF. These artifacts have, in contrast to the rest of the LSF clasts, very sharp edges. They are made of chert, derived from layered cherts in the ephemeral saline lake sediments which also form part of the lag deposit in the LSF. These sharp-edged artifacts have clearly not been transported very far. The different relative ages (Middle as well as Late Stone Age) of the artifacts suggest that not all of them were manufactured before the deposition of the Gordonia Formation, but they probably worked their way down through the unconsolidated sands of the Kalahari to the top of the existing LSF.

Moeyersons (1978) proved by experiments on unconsolidated Gordonia Formation, that it is entirely possible for large clasts to migrate down the sand profile due to bioturbation. Fluvial processes in Late Kalahari times could have scattered clasts and/or artefacts over the sands undergoing bioturbation, subsequently making their way down the sandy soil profile. Scattered artefacts and pebbles in the Late Kalahari Gordonia Formation above the LSF, seem to support this interpretation. This mechanism would only be valid in areas where the unconsolidated, Late Kalahari sands are not very thick (maximum of 3 metres in the study areas) and where there is an absence of calcrete layers in the Makoba Subgroup sands.

Grains smaller than a critical size (not yet determined) tend to migrate upwards in the soil profile due to bioturbation by ants. The critical size of the upward-migrating grains probably depends on the maximum grain size that the ants (or other organisms) can transport.

At least three mechanisms are therefore thought to be responsible for the deposition of the LSF (Fig. 14).

(1) A residual lag formed during a long period of non-deposition, while the landscape was lowered by more than 25 metres (Orapa - Letlhakane area).

(2) Gravity flow down the slopes of palaeo-highs.

(3) The addition of clasts to the LSF through bioturbation. This process is probably still going on in some places, as scattered pebbles and stone artefacts have been found in the Gordonia Formation above the Letlhakane Stoneline Formation.

#### (5.2.3) Debe Calcrete Formation (Orapa-Letlhakane Area)

Calcretes that cover the LSF are mostly hardpan (as described by Goudie, 1983) with a cap of laminar calcrete that has a maximum observed thickness of 10 cm. Minor nodular and honeycomb calcrete also occur (See section 7). Classification, however, is hampered by calcretes that form composite profiles in the study areas.

In the Orapa-Letlhakane Area, as in all the study areas in northern Botswana, the Makoba Subgroup is compressed. The calcrete members that are well separated by sand members in the south-west of the study areas, where a thick sequence of Late Kalahari sediments is developed, have coalesced, to firstly calcretize the LSF and later to form a thick calcrete on top of the LSF. In only one place in the South Sua Pan Area (Fig. 3d), two thin (less than 5 cm), unconsolidated fine- to coarse-grained sand beds still separate the calcretes. The calcretes had a displacing effect on the clasts of the LSF. LSF clasts that were probably in contact with each other in the lag deposit are now up to 3 cm apart.

#### (5.2.4) Gordonia Formation (Orapa-Letlhakane Area)

The unconsolidated, oxidized, reddish brown, bioturbated, fine- to coarse-grained sand of the Gordonia Formation is spatially extensive and covers all the lithologies except the Makgadikgadi lake sediments. The sand attains a maximum thickness of 3 metres in this study area. A few degraded and vegetated linear dunes were found in the southern and south-eastern parts of the Orapa-Letlhakane Area. The sand has same the characteristics as described in section 3.1.7.

### (5.3) South Sua Pan Area (Fig. 3d)

This area lies adjacent and to the east of the Orapa - Letlhakane Area. There is some overlap between the two maps.

#### (5.3.1) Profile at F (South Sua Pan Area)

Three profiles were constructed through an Early Kalahari age graben at F, based on field work, detailed drilling, ground magnetic as well as gravity surveys. The graben at F (South Sua Pan Area) clearly illustrates an Early Kalahari basin that formed as a result of block-faulting.

The effects of the Kalahari block-faulting are illustrated in the profiles (Figs. 16, 17, 18 and 19) and the plan view (Fig. 15). The NW-trending graben has a dolerite dyke on its south-western edge which is coincident with a major fault. This is a fairly common feature in the Orapa-Letlhakane (Fig. 3c) and South Sua Pan (Fig. 3d) areas.

Alluvial fan and braided stream deposits dominated the initial in-filling of the basin. The Early Kalahari graben at F also shows the amount of throw on Early Kalahari faults commonly found in the study areas. The floor of the main NW trending graben was broken up into smaller horsts and grabens and as a result, the initial transport of sediment was of a local nature. However, as the main NW trending basin was filled in, sediments were transported from further afield and the transport became both perpendicular and parallel to the main NW - SE trending fault that defines the south-western edge of the graben.

To the south-west of this major fault (Fig. 15), the Ntane Formation has only a thin cover of calcrete (maximum of 50 cm) and unconsolidated Gordonia Formation (maximum 60 cm) (Fig. 18). Further south, another dolerite dyke joins the one coincident with the main fault (Fig. 15). Some of the Karoo age, fluvial Ntane Formation sandstones are superficially similar to the Mmashoro Formation sandstones and Stansfield (1973) mistook some Mmashoro Sandstone for Ntane Sandstone in the South Sua Pan area. On closer inspection significant differences appear.

In hand specimens and thin sections, the principal differences between the fluvial Ntane Formation (Sample PdP/Nt/V1, Appendix 1) and fluvial, Early Kalahari sediments of the Mmashoro Formation in the study areas are:

Ntane Formation:

Mmashoro Sandstone Formation:

1. Thin section studies (Plate 34) show concavo-convex as well as sutured contacts, due to pressure solution and compaction.

2. There is a complete lack of kimerlitic heavy minerals and a depletion of heavy minerals in general.

3. Sorting is generally very good.

4. Bioturbation is scarce and mostly of the Scoyenia or Planolites types.

5. When hit with a hammer, the sandstone will usually break through the grains.

1. No pressure solution was seen in the studied thin sections (Plates 25, 27, 31 and 32).

2. Kimerlitic heavy minerals can often be found and heavy minerals are relatively abundant compared to the Ntane Formation.

3. Sorting is generally moderate to poor.

4. Bioturbation is common and mostly of the Thalassinoides type.

5. When hit with a hammer, the sandstone will usually break around the grains.

In thin section, the fluvial Ntane sandstone shows pressure solution in the form of concavo-convex contacts and where pressure solution was more intense, the contacts between grains became sutured as the result of compaction (Plate 34).

The main difference between the fluvial Ntane sandstone and the fluvial Kalahari Group sediments is therefore the amount of compaction undergone by the sediment. Another major difference is the lack of kimerlitic heavy minerals (from the Cretaceous kimerlites) in the Ntane sandstone. Most of the Ntane Formation however, consists of well sorted aeolian sandstone and is easy to distinguish from the fluvial or lacustrine Kalahari Group sediments.

The north-easterly edge of the NW trending Kalahari graben is also defined by a fault (Fig. 3d), with mudstones of the Mosolotsane Formation outcropping on its north-eastern side.

The floor of the NW trending graben was broken up into a number of smaller blocks, some of which have been tilted (Figs. 15 and 18).

The sediments of the Mmashoro Sandstone Formation first filled in the small grabens within the major NW trending graben. In the close proximity of faults, coarse-grained to conglomeratic alluvial fan sediments dominate. These coarse-grained sediments grade downslope into finer-grained, streamflow sediments. The red siltstones have been produced partly by the weathering and erosion of Drakensberg basalt. The erosion of red Mosolotsane mudstones to the east and north of the Kalahari graben must also have played a major role in the formation of the red Kalahari siltstones.

The fining-upward sequence of fluvial sediments, with conglomerates and gritstones at the base and fine-grained sandstones and siltstones at the top, is overlain by fine- to coarse-grained, moderately bioturbated fluvial sandstone, which is in turn overlain by the LSF. Transport directions were measured from low-angle and trough cross-bedding in this coarse-grained fluvial sandstone in trenches at 1, 2 and 3 (Fig. 15). In trench 2 the sandstone also contains a large number of sub-rounded to sub-angular basaltic clasts that decrease rapidly in size to the north and north-east. The results of detailed drilling and palaeocurrent directions indicate that, at this stage in the history of the depositional basin, transport was both parallel and perpendicular to the NW trending faults that defined the boundaries of the Early Kalahari graben. Bioturbation of the sandstone was poor and only a few *Tigillites* trace fossils were found in the trenches. The nature and scarcity of the trace fossils as well as the good preservation of primary sedimentary structures, such as trough- and low-angle cross bedding, suggest that the oxidized Mmashoro Sandstone in the graben is of a fluvial nature.

The denudation that resulted in the formation of the LSF must have removed any lacustrine sediments that formerly covered the fluvial sediments in the graben.

The Gordonia Formation here consists of only a thin (< 1.5 m) cover of unconsolidated aeolian (with minor fluvial) sand.

Fault control on the distribution of the Mmashoro Sandstone Formation as a whole, can be seen clearly in the South Sua Pan Area where block-faulting dominates the landscape. Horsts with outcropping Karoo lithologies are separated by faults from grabens up to 60 metres deep (borehole information) in which conglomerates and sandstone of the Mmashoro Sandstone Formation are preserved. Due to block faulting, the thickness of the



Mmashoro Sandstone Formation varies in the South Sua Pan Area from less than one metre, to approximately sixty metres (borehole information).

#### (5.3.2) Dikara conglomerate at P11 (South Sua Pan Area)

Light grey to light brown, calcreted, matrix-supported conglomerate of the Dikara Member overlies pale to dark green siltstones of the Mosolotsane Formation (section 2.2.3.1), at P11. The conglomerate consists of angular to sub-rounded pebbles, derived from the underlying Mosolotsane Formation, in a sandy and clay-rich matrix. Quartz (61%) dominates, while clay minerals make up 10% of the matrix. Minor plagioclase and hypersthene sand grains also occur. The sorting of the sediment is poor.

Calcium carbonate, in the form of sparite (thin section PdP/BK/V1, Appendix 1), forms the cement in the conglomerate. The diagenetic, calcium carbonate cement has not only corroded and replaced some of the clay minerals in the matrix, but also corroded the Mosolotsane siltstone clasts, plagioclase, hypersthene and quartz clasts found in the sediment. Calcrete in the form of sparite in-filled and probably widened cracks in the sediment through its replacive and displacive effects.

The presence of iron oxide in the sediment suggests sub-aerial deposition. The large siltstone clasts in the conglomerate are derived from the underlying green Mosolotsane Formation, which outcrops to the east and west (South Sua Pan Area). The sub-angular plagioclase and hypersthene are probably derived from the Karoo basalt or Post-Karoo dolerite dykes. The immature nature and angularity of the clasts in the sediment suggest a proximal position for the sediment in the depositional basin. The poor sorting and roundness as well as the clay-rich nature of the conglomerate suggest rapid deposition, possibly as part of a debris flow. Unfortunately, the outcrop is too poor to make conclusive determinations.

#### (5.3.3) Profile at E (South Sua Pan Area)

At E (Fig. 20), a thickness of approximately three metres of the Mmashoro Sandstone Formation is exposed on the edge of a pan. The fine- to medium-grained, brown, oxidized sandstone with a few scattered outsize pebbles, shows some evidence of bioturbation in the form of *Thalassinoides* trace fossils and faint traces of low-angle cross-bedding.

Although the low-angle cross-bedding indicates relatively fast current velocities, the *Thalassinoides* trace fossils are characteristic of low-energy environments. The oxidized sandstone is therefore interpreted to be of a fluvio-lacustrine

nature. Although initial sedimentation may have taken place in a fluvial or beach environment, bioturbation probably took place in a lacustrine environment. As mentioned in section 5.3.1. the denudation that resulted in the formation of the LSF probably removed the cover of lake sediments. Alternatively, flash floods followed by quiet periods in the same environment is a possibility.

The paucity of outcrops and the large distances between them defies lateral correlation of the Mmashoro Sandstone Formation in the South Sua Pan area as a whole.

#### (5.3.4) The Letlhakane Stoneline Formation at D and borrow-pit 14 (South Sua Pan Area)

At D, the LSF overlies and consists entirely of sandstone clasts of the Ntane Formation (Plate 11). The LSF has been ferricreted in this locality, as elsewhere in northern Botswana. In borrow-pit 14, on the Orapa - Francistown road, the LSF is unconsolidated (Plate 12), calcreted as well as ferricreted, all in the same outcrop.

The calcrete has displacive and replacive effects on the LSF clasts, giving the LSF a matrix-supported appearance (Plate 13). These displacive and replacive effects of the calcrete were also seen in other lithologies in the study areas (Plates 16 and 17). The ferricrete only cements the clasts and it does not have such a pronounced displacive effect as the calcrete.

In the ferricreted LSF at D (Plate 11), stone artefacts, presumably MSA (Middle Stone Age), were also cemented. This indicates a relatively young age for the ferricrete formation.

In some localities in the study area, such as the Letlhakane Mine, a karst surface is developed in the calcreted LSF (Plates 14 and 15). This karst surface is considered to be the result of wetter climatic conditions that dissolved the calcrete. Pebbles above this karst surface show iron oxide coatings, while those embedded in the calcrete are clean (Plates 7 and 8). This shows that the calcrete preceded the ferricrete at the Letlhakane Mine (Fig. 3c). It therefore appears as if ferricretes are currently (or in the recent past) developing in the study area, while the calcretes are going into solution.



(5.3.5) The Letlhakane Stoneline Formation in borrow-pits along the tar road between Orapa and Francistown (South Sua Pan Area)

The LSF in borrow pits 10 to 14 contains clasts of agate, carnelian, quartz, Ntane sandstone and Mmashoro sandstone (Table 2).

Because the LSF is considered to be derived from erosion and weathering of more than 25 metres of the underlying lithology, and assuming that the LSF has not undergone substantial transport, the clast types indicate the former presence of the Mmashoro Sandstone Formation in this area. The basaltic and Ntane clasts are probably reworked detrital clasts of the Kalahari Group. The clasts found in the LSF give an indication of palaeo-transport directions into this Early Kalahari graben. To the west and east, Ntane sandstone crops out. Since the LSF consists entirely of Ntane sandstone clasts in these areas, it can be safely assumed that the Mmashoro Sandstone Formation did not cover these areas. They were probably horsts that were eroded providing material to in-fill the Early Kalahari graben. The basaltic clasts were probably derived from Drakensberg basalt that covered the Ntane Sandstone Formation in pre-Kalahari times. A considerable amount of erosion must therefore have taken place during deposition of the Mmashoro Sandstone Formation.

From Table 2 it can be seen that in the LSF in borrow-pits along the road, there is an increase in the proportion and size of Ntane sandstone clasts eastward from 14, with a simultaneous decrease in the proportion and size of clasts derived from the Drakensberg basalt. The proportion and size of clasts derived from the Mmashoro Sandstone Formation remain constant.

At borrow-pit 14, the dominance of clasts derived from the Drakensberg basalt (the nearest possible source being the Drakensberg basalt that formerly covered the block of Ntane to the west) strongly suggests the major influx of sediment to have been from the west at this locality. It also suggests that the Drakensberg basalt was already eroded away (or never existed) on the block of Ntane to the east, as substantial amounts of sediment have been brought into the graben from the horst of Ntane sandstone in the east. Transport from the south and north seems to have been of minor importance at borrow-pit 14.

Resistant clasts in the LSF therefore give an indication of the nature of the lithology that has been removed by the processes producing the LSF. If some of these resistant clasts were detrital clasts in the Mmashoro Sandstone, they may be of use in determining palaeo-transport directions.

(5.3.6) Debe Calcrete Formation (South Sua Pan Area)

Composite profiles of calcrete with a maximum thickness of 1.5 m were found in the South Sua Pan Area. Very often the calcretes have been partially or completely dissolved due to subsequent wetter climatic conditions. Calcretes, where developed, consist of powdery, nodular, honeycomb, hardpan and layered hardpan calcrete. As described in section 5.2.4. the calcretes have a displacing effect on the LSF.

#### (5.3.7) Gordonia Formation (South Sua Pan Area)

The Gordonia Formation crops out extensively in the South Sua Pan Area. The northern limit of its distribution is the Mosu scarp. The thickness is usually less than one metre, but thicknesses of up to 3 metres have been found in boreholes.

A number of vegetated palaeo-pans of Late Kalahari age are developed in the South Sua Pan Area. These pans are underlain by the LSF and contain abundant dark, clay-rich sediment, which has a stunting effect on the Mopane shrubs growing in them. The majority of these palaeo-pans are developed on a horst of Ntane sandstone and can be easily identified on SPOT and Landsat TM images.

#### (5.4) Nata Area (Fig. 3e)

The effects of tectonic control (caused by block-faulting) on the distribution of the Mmashoro Sandstone Formation and Makgadikgadi lake sediments is clear from the Nata Area map, as the easternmost boundary of the Makgadikgadi lake sediments is a fault-controlled feature. Several beach ridges at specific elevations (Cooke, 1979, 1984, Shaw, 1985, 1988), occur in the Makgadikgadi lake sediments.

##### (5.4.1) Profile of the Mmashoro Sandstone Formation (Orapa Subgroup) at A (Nata Area)

At profile A (Fig. 21), Mmashoro Sandstone crops out in the Tsatokwe River. The reddish brown colour of the sandstone is related to iron oxides such as hematite and goethite. Characteristically these iron oxides are formed in soils under weakly acidic to alkaline conditions, with good drainage, in warm, sub-humid to arid climatic conditions (Reineck and Singh, 1980).

The nature of the oxidized, consolidated sandstones at A, suggests deposition by ephemeral braided streams. Present-day ephemeral streams in semi-arid to arid environments are characterized by sporadic and abrupt fluvial activity as well as by a low water/sediment ratio. The major bedforms are bars, megaripples and small ripples, producing different types of cross-bedding (Reineck and Singh, 1980).

Discontinuous deposition with erosion, characterized by erosional upper and lower contacts, was observed in the sandstone. The lower parts of beds are impoverished in trace fossils and characterized by parallel-laminated sandstone. Bioturbation increases upwards in each bed and the top of the bed shows erosional truncations of burrows.

The most striking feature at profile A, is the undulating bedding and channels (up to 4 metres wide and 1 metre deep) scoured into the sediment. The present Tsatokwe River cuts through the sandstone to form an outcrop in which individual beds can be traced out for at least 50 metres. The undulating bedding is thought to be the result of alternating cycles of desiccation and wetting, indicating wet and dry periods. Numerous other features described below, support an ephemeral braided stream interpretation for the deposit.

A number of sequences in the sandstone which show a decrease in the scale of sedimentary structures upwards, probably represent deposition during relatively short periods of strong flow following intense showers. Each sequence is separated from the underlying one by large scour troughs which are parallel to the north-easterly palaeo-transport direction. The palaeocurrent directions were obtained by measuring the trough axes of ten trough cross-bedded sets as well as the axis of channels in plan view. There is little variation in the palaeo-currents measured and a unimodal down-palaeoslope dispersal pattern with variances below 200 emerged. Unfortunately, no other suitable outcrops were found to obtain palaeocurrent directions over a larger area.

The scoured basal contact is overlain by upper plane beds (high flow regime), which are succeeded by large scale trough cross-beds (high to intermediate current velocities). These decrease in size upward, grading into small scale trough cross-bedding and eventually ripple lamination indicative of deposition from waning currents. The grain size does not change markedly upwards, and the sandstones can all be classified as fine- to medium-grained.

Moderate to poor bioturbation is evident in the sediments. Trace fossils are isolated and of a different type than the *Thalassinoides* trace fossils described for the Orapa and South Sua Pan areas. The trace fossils are classified as *Tigillites* on a purely morphological basis. They occur as isolated, vertical shafts of uniform diameter. At A the diameter of the trace fossils is two to three centimetres. The backfilled burrows are generally coarser-grained than the surrounding sediments and white in colour, due to an abundance of carbonate in the burrows. Since the nature of the deposit suggests rapid deposition of the fine- to medium-grained sandstone in a high energy fluvial environment - most of the bioturbation must have occurred shortly after the deposition of each sequence. This suggests that enough time elapsed between flood events to allow moderate bioturbation.

Successive flood events eroded some of the underlying sediments and caused erosion of a number of burrows, although some escape tubes were observed. This is strong evidence for the ephemeral nature of the stream, because the complete absence of surface lebensspuren, associated with evidence of intermittent erosion, is typical of such an environment. As mentioned above, laminae truncating trace fossils and trace fossils grading into escape structures are also evidence for bioturbation contemporaneous to penecontemporaneous with sedimentation.

The trough cross-beds, which are more than 20 cm wide and 4 cm thick (Fig. 22), are interpreted to have been produced by migrating megaripples at intermediate to high current velocities.

Ripple foreset lamination (less than 4 cm in thickness) was produced by migrating small ripples, representing relatively low energy conditions.

The sediments of the Mmashoro Sandstone Formation overlie both Archaean Basement rocks and Karoo basalts in the Nata Area (Fig. 3e). The Mmashoro Sandstone Formation was traced out southward for two kilometres and eastward beyond F (Nata Area, Fig. 3e). In the west, it is cut off (and apparently thrown down) by a fault, which is probably related to the Makgadikgadi lake sediments to the west of the fault. This fault defines the eastern boundary of the Makgadikgadi lake sediments in the Nata area. As mentioned in section 3.2 the deposition of the Makgadikgadi Subgroup falls beyond the scope of this thesis. In A, the Makoba Subgroup sediments have been eroded away by the present river but everywhere else the LSF, calcretes as well as the unconsolidated sand of the Gordonia Formation, overlie the Mmashoro Sandstone Formation.

#### (5.4.2) LSF in the Nata Area

The Letlhakane Stoneline reflects the local bedrock lithology and consists of subrounded, poorly sorted clasts of granite and metamorphic rocks of the Basement Complex, agate and quartz of the Drakensberg basalt and poorly sorted brown sandstone of the Mmashoro Sandstone Formation, where it overlies these lithologies. The LSF has a maximum thickness of 30 cm and is unconsolidated, but for a few places where it is calcretized.

#### (5.4.3) Debe Calcrete Formation

In a few localities remnants of a hardpan calcrete which has a displacive effect on the LSF clasts, were found. In most places, the calcrete is completely dissolved. However, calcretes are common in the Makgadikgadi lake sediments, which are not discussed in this thesis.

#### (5.4.4) Gordonia Formation

Unconsolidated, reddish brown, fine- to medium-grained sand with a maximum thickness of one metre of the Gordonia Formation covers the whole Nata area, except for the area underlain by Makgadikgadi lake sediments.

## (5.5) Mmashoro Area (Fig. 3f)

### (5.5.1) Introduction

In the Mmashoro Area, there is evidence for the existence of a saline lake in Early Kalahari times, which was fed by braided streams developed on broad sandflats. With time, the saline lake extended laterally to cover the braided stream deposits of the adjacent sandflats. The lake finally dried out sufficiently to produce layered cherts, similar to those described for the Orapa-Letlhakane Area at A (section 5.2.1). The landscape denudation reflected in the LSF, removed most of these layered saline lake deposits. Resistant chert clasts remaining in the LSF over large areas confirm the former presence of a lake. The whole area was then covered by Late Kalahari sand of aeolian and fluvial origin.

Rejuvenation of the tributaries of the Limpopo, (possibly due to tectonic lowering of the base level in the lower Limpopo, related to movement of the East African Rift), caused erosion of the Kalahari Group to expose Drakensberg basalt to the north of the scarp. The latter also forms the northern boundary of the LSF and the in situ Gordonina Formation.

### (5.5.2) Profile at A1

At A1, fluvio-lacustrine sediments of the Mmashoro Sandstone Formation overlie Drakensberg basalt with an erosional contact (Fig. 23). As will be discussed below, the primary sedimentary structures indicate streamflow, but the bioturbation indicates shallow lacustrine conditions shortly after deposition.

Scour troughs, up to 50 cm deep and 120 cm wide, have been eroded into the basalt. The top 150 cm of the basalt shows advanced weathering and is moderately calcreted, indicating a substantial post-Karoo - pre-Kalahari period of sub-aerial exposure and non-deposition. Clasts eroded from the basalt also include calcrete, agate and carnelian pebbles, which occupy the scours in the basal part of the Mmashoro Sandstone Formation. These channel-fill conglomerates at the base of the Kalahari Group, here called the Dikara Member of the Mmashoro Formation, gradually decrease in thickness downslope to eventually disappear in the distal part of the basin (see section 5.5.3) at B1 and B2. The bedrock slope between A1 and B1 is gentle with the base of the Kalahari Group at B1 approximately 5 metres below A1.

The basal scour-and-fill deposits are overlain by low-angle cross-bedded, fine- to medium-grained, moderately to poorly sorted brown sandstone. This bed is in turn overlain by a red to white, sandy silt bed. These three units form the first of



four fining-upward sequences in the Mmashoro Formation sediments at A1 (Fig. 23) (Mmashoro Area, Fig. 3f).

The rest of the profile shows trough cross-bedded, fine- to medium-grained, moderately to poorly sorted, brown sandstone with a few red sandy silt beds. The latter represent the end of flood sequences. In the profile at A1 (Mmashoro Area), the presence of saline minerals such as gypsum, records the semi-arid climate that prevailed during deposition (Plate 19).

From the base to the top of the Mmashoro Sandstone Formation at A1 (Fig. 23), a decrease in energy and therefore current velocities is evident in an overall upward decrease in thickness of the trough cross-bedded sets. Since the grain size of the sandstone is more or less constant, the current velocities must have decreased to the top. This could be the result of the in-filling of the graben by the ephemeral braided streams and the resultant decrease in slope or alternatively, waning currents. However, the layered cherts that form the top of the Early Kalahari succession in the Mmashoro Area (section 5.5.3), suggests that the lake dried out sufficiently to become hypersaline. The Mmashoro Sandstone therefore appears to show a drying-upward sequence.

Some beds, such as the red, sandy silt layer (unit 8) (Fig. 23) at the top of the basal sequence, can be traced laterally for more than five kilometres and were found as far east as A2 and as far north as D (Mmashoro Area). At A2, unit 8 has graded into a finer-grained, red siltstone (Plate 18).

The trough cross-bedded sandstone beds at A1 pinch out laterally. These lenses are up to 10 metres wide. Unit 10 often shows mud rip-up clasts in its lower part, eroded from units 8 and 9, at A2.

The trough cross-bedding shows a more or less constant NNW palaeocurrent direction at A1, A2 and D and at the localities in-between these positions. The palaeocurrent directions were obtained for each locality in the study areas, by measuring the trough axes of at least ten trough cross-bedded sets in plan view. A unimodal down-palaeoslope dispersal pattern with variances below 500 emerged.

The trough cross-bedding indicates deposition in lunate dunes, except for the top of sequence 4, where deposition took place as small ripples. The latter have an average length of 27 cm and height of 3,5 cm.

The bioturbation increases dramatically from the bottom where isolated, vertical shafts of uniform diameter (Tigillites) occur, to the top of the succession where bioturbation has taken the form of irregular 3-D networks of tunnels and shafts with variable diameters (Thalassinoides). (These trace fossils were classified on a purely morphological basis). Near the top of the succession the burrows cross-cut erosional upper and

lower contacts of trough cross-bedded sets. This indicates bioturbation subsequent to deposition. The strong upward increase in intensity and the nature of the bioturbation (Thalassinoides trace fossils) near the top of the succession suggest an expansion of the wet lacustrine conditions (see section 5.5.3).

The depositional history interpreted for the sediments at A1 and A2 is the initial basinal in-filling by single, fairly straight channels. As the basin was in-filled, progressively lower energy conditions prevailed and the distal lacustrine environment (described for B1 and B2 in section 5.5.3) prograded to cover the oxidized fluvial sediments at A1 and A2. Shallow lacustrine conditions must have prevailed because the sandstone at the top of the succession at A1 is still as oxidized as the underlying fluvial scour-and-fill deposits. Evidence for the lake expansion can also be seen in the clasts of layered chert in the LSF in the vicinity of A1 and A2. The rhythmites were however only thinly developed and the landscape denudation that produced the LSF destroyed this deposit so that only the more resistant chert survived in the LSF.

The sediments at A1 and its environs which show a change from fluvial sediments at the base to shallow lacustrine conditions at the top of the succession are therefore interpreted to be fluvio-lacustrine deposits.



### (5.5.3) Profile at B1 and B2 (Mmashoro Area)

The fluvial sediments at A1 and A2 grade downstream into saline lake sediments of the Mmashoro Formation at B1 and B2. In this locality the basal conglomerate (Dikara Member) found at A1 is absent and massive, bioturbated, lacustrine sandstone lies directly on weathered and calcreted Drakensberg basalt.

The lake sediments that overlie the Drakensberg basalt (Fig. 24) appear massive due to bioturbation, but faint horizontal bedding is sometimes visible in the white to grey, fine- to medium-grained sandstone that lacks iron oxides in the matrix of fresh rock specimens. This lack of iron oxides is in contrast to the fluvio-lacustrine sediments described in sections 5.5.2.

Bioturbation was much more intense in these low energy lake deposits (Fig. 24) than in the intermediate to high energy fluvio-lacustrine deposits at A1, A2, D and the fluvial deposits at C (Fig. 25). In the fluvial sediments, bioturbation is poorly to moderately developed in the sandstones, with abundant bioturbation in the silty beds. In the lake sediments that overlie Drakensberg basalt at B1 and B2, bioturbation was intensive (Plates 20, 21, 22, 23 and 24), increasing upward. About two thirds up the lake sediment profile, bioturbation is so intensive that no undisturbed sediment remains (Plate 24), indicating still water conditions. Higher up the profile, bioturbation decreases rapidly and disappears below the layered cherts. During the very saline conditions in which the layered cherts were deposited, no burrowing organisms could survive. The only signs of life are the small stromatolites in the upper parts of the lake profile.

At the top of the lacustrine succession at B1, layered cherts similar to that of the Mmashoro Sandstone Formation (Profile A, Orapa-Letlhakane Area), are associated with small (4 cm high and 10 cm wide), dome-shaped stromatolites (Samples PdP/JPLR/LK/Hill/Strom 1, PdP/JPLR/LK/Hill/Strom and PdP/JPLR/LK/Hill/LS, Appendix 1). The stromatolite layering is irregular and partly accentuated by colour differences. The irregularity of the layering helps to differentiate laminated sediments formed from algal mats (such as these) from those laminated sediments formed by physical processes. The laminae form crinkly structures and sometimes build low domes.

The laminations consist of alternating lighter and darker micritic layers that contain scattered sediment grains. Micrite make up 90% of the stromatolite composition, with 4.4% detrital grains. In some areas the micrite has a vaguely pelleted structure, which is characteristic of stromatolites (Adams et al., 1991).

Laminoid fenestrae (pores elongated parallel to the bedding, which are larger than grain-supported spaces and filled in by

internal sediment or cement; Adams et al., 1991), also characteristic of stromatolites, are common in the thin sections. These laminoid fenestrae may form from the decay of organic matter associated with algal stromatolites (Adams et al., 1991).

The scattered fine sand grains in the micrite are sedimentary particles trapped and bound by the algal mats.

Oncoids (larger than 2 mm) presumed to be blue-green algae coating grain surfaces, trap and bind fine sediment particles and are abundant in some parts of the thin sections. The asymmetrical growth and the wavy nature of the oncoid laminae, as well as some micrite particles that have grown together to form compound grains, confirm the algal nature and origin of these grains. Peloids (grains composed of micrite and lacking any recognizable internal structure, often formed by the total micritization of algae) were also found in the thin sections (Plate 33).

Inorganic oncoids and pisoids, in contrast, have regular concentric laminae and compound grains are unlikely to occur, because precipitated carbonate laminae are formed while the grains are held in suspension. The algae-related carbonate grains also often contain a number of sediment grains, while inorganic carbonate grains usually contain only one sediment grain at their centre (Adams et al., 1991).

Two generations of silica cement in the form of chalcedony make up 5.6% of the stromatolites. The first formed continuous colloform overgrowths on grains, (similar to the calcium carbonate in thin section PdP/BK/B2, Appendix 1, taken from sandstone seven metres above the base of the succession at B1 and B2), with the second filling in the remaining voids. It is thought that the first generation of silica precipitated contemporaneously or penecontemporaneously with the sediment, because the stromatolitic deposits grade laterally into and are overlain by layered cherts. This first generation of silica precipitation was followed by shallow water conditions or sub-aerial exposure of the sediment, resulting in the iron-oxide precipitation on the continuous overgrowths of silica. Silica subsequently filled in the remaining voids.

Bioturbation in the form of three-dimensional networks of tunnels, generally have diameters of about 0.5 - 1 cm. The branched burrows and tunnel systems with Y-shaped forkings, and lacking surface ornamentation, commonly widen to form pear-shaped cavities. These are classified as *Thalassinoides* (Häntzschel, 1962).

In the Mmashoro lake sediments, however, another type of trace fossil occurs. These are cylindrical vertical shafts (some backfilled) about 2 cm in diameter, with lateral tunnels of the same diameter, branching off at right angles, parallel to the horizontal bedding planes. They are possibly *Lennea*, as

described by Häntzschel (1962). These large-diameter trace fossils have only been found in the lacustrine sediments

In outcrops the trace fossils form hollow tubes (Plates 20 and 21) due to rainwater that firstly leached out the carbonate and then bleached the sidewalls of burrows to form white "halos" around the trace fossil. In fresh rock specimens the trace fossils are in-filled (Plate 10) and generally contain more carbonate than the surrounding sediment. Higher up in the profile at B1 and B2 where silica became dominant over carbonate, the trace fossils contain more silica than the surrounding sediment and weather positively (Plate 24). The trace fossils therefore give a good indication of how the composition of the lake water changed from initially rich in carbonate (or clay minerals that could produce carbonates) to rich in silica towards the end of clastic deposition in the lake. The backfilled trace fossils have a cement different from that of the surrounding sediment due to the fact that burrows would have provided routes for the overlying saline lake water to penetrate into the sediment.

Occasionally the in-filled trace fossils have smaller grain sizes with better sorting than the surrounding sediment. This is possibly due to the ingestion of only certain grain sizes by the organisms, or due to better sorted overlying sand in-filling open burrows.

At B1 and B2 deposition had been discontinuous, but although the rates of deposition varied, no erosion took place. Discontinuous sedimentation with no erosion can be recognized in the bedding planes with relatively undisturbed surface openings of burrows (Plates 22 and 23). Small heaps of sand pushed out at the openings of the burrows can be found on some bedding planes. The little mounds appear to have been washed by the next influx of water and sediment to form linear features, parallel to the current, consisting of coarser grains than on the surrounding bedding plane. Conditions were however calm enough not to erode the openings of burrows.

The bedding plane in Plate 22 formed because of the settling out of finer, slightly darker, silty material between times of major sand accumulation. Deposition of the thick sand beds have however been slow enough for bioturbation to continue uninterrupted as the beds contain numerous trace fossils (Plates 20, 21 and 22), none of which grade into escape structures. Burrows often cross-cut the few still recognizable bedding planes.

In thin sections (Samples PdP/BK/B1 and PdP/BK/B2, Appendix 1), the sandstone close to the underlying basalt shows a clay-rich matrix in which carbonate dominates over silica, but higher up in the sequence, the clay and carbonate matrix is replaced by silica, as conditions became more saline towards the top (under these very saline conditions, silica first went into solution and later precipitated as described in section 5.2.1). From

the bottom to the top of the lacustrine succession at B1 and B2, there is a decrease in the size as well as the number of clasts derived from the Karoo basalt. The roundness and sphericity of these basaltic clasts increase towards the top. The sandstone grains in general, in thin section PdP/JPLR/Hill/Strom 1, are better sorted than in thin section PdP/BK/B2. Of the grains derived from the Karoo basalt, only small sub-rounded to rounded plagioclase grains remain. PdP/JPLR/Hill/Strom 1 therefore represents a more mature sediment in terms of grain composition.

The upward increase in bioturbation in the lower two thirds of the profile at B1 and B2 is interpreted to be an indication of deeper water. The saline lake then started to dry out, so that conditions became more saline and the burrowing organisms died out.

The stromatolites indicate shallow, marine-like conditions, with little or no sedimentation prior to the final desiccation and the formation of chert rhythmites in the lake. Therefore, at the time in the depositional history that these stromatolites formed, the fault controlled basin in the Mmashoro Area was completely in-filled and evaporation caused high concentrations of salts in the remaining water, sufficient to mirror marine conditions. With continued evaporation, the pH would rise high enough for silica firstly to go into solution and with continued evaporation to precipitate in the form of chert and/or opaline silica. Typically, the stromatolites grade laterally into and are overlain by chert/opaline silica and laminoid fenestrae are also in-filled by silica. The continuous, colloform overgrowths of silica on grains as well as concentric algal remains filled in by silica, may be the result of such contemporaneous precipitation of silica with sedimentation. The second episode of silica precipitation that filled the remaining voids is probably a diagenetic feature.

#### (5.5.4) Profile in road-cut at C (Mmashoro Area)

At C, fluvial sediments, showing a transport direction away from the saline lake, can be seen (Mmashoro Area). At this locality, the Mmashoro Sandstone Formation overlies weathered and calcreted Drakensberg basalt with an erosional contact (Fig. 25). The basal conglomerate consists mostly of calcrete clasts (up to 3.5 cm long), with a few basalt, agate, carnelian and quartz clasts. The clasts are sub-rounded to sub-angular, set in a brown sandy matrix containing angular to rounded quartz and feldspar grains as well as some angular basalt grains. The matrix is texturally immature and clay-rich. Although a large part of this material may have been derived from the basalt, the well-rounded quartz grains must have a different provenance (Sample PdP/BK/C1, Appendix 1).

The 70 cm thick basal conglomerate grades upward into brown, fine- to medium-grained, massive sandstone, (Fig. 25) (Sample PdP/BK/C2, Appendix 1), which shows some Tigillites bioturbation. Generally, however, rapid deposition and erosion reduced the animal population and density of bioturbation so that the sedimentary structures are better developed in these fluvial Mmashoro Formation sediments.

The 60 cm thick massive sandstone bed is overlain by 20 cm of red, sandy mudstone showing moderate bioturbation. The burrows are filled in by brown, fine- to medium-grained sandstone. This bed is interpreted to be the top of the basal sequence, representing still water conditions at the end of a flood event where bioturbation could continue undisturbed.

The overlying brown, fine- to medium-grained sandstone (Sample PdP/BK/C3, Appendix 1) reflects erosion of this argillaceous bed, as can be seen in the abundant red mud rip-up clasts (up to 1 cm in size). This 28 cm thick sandstone bed shows some bioturbation, but here the burrows are filled in by red, oxidized, sandy mud. The bed appears massive, but might well show cross-bedding upon x-ray investigation.

The 57 cm thick sandstone bed overlying the massive bed has the same characteristics, except for the red mud rip-up clasts, which are smaller in size (<0.5 cm).

This sandstone bed is in turn overlain by faintly trough cross-bedded, fine to medium, brown sandstone, with some bioturbation and a thickness of 36 cm. This bed is more thoroughly silcreted than the rest of the profile.

The topmost bed is a 30 cm thick, trough cross-bedded, brown sandstone (Samples PdP/JPLR/5 and PdP/BK/C4, Appendix 1) (Plate 32). Transport directions were in a south-westerly direction (Mmashoro Area, Fig. 3f). The bedding is typically lens-shaped and can be followed laterally for about 10 m.

The red, sandy clay lenses are interpreted as abandoned anabranches in a braided stream environment, filled in by slow sedimentation after avulsion. As can be expected, bioturbation is common in these beds. With the next flood event, the clay deposits were eroded and mud rip-up clasts were deposited in the overlying sediments. The presence of red clay flakes and clay pebbles provides good evidence for sub-aerial exposure of water-lain sediments (Reineck and Singh, 1980).

In thin sections, the sediments of profile C show a slight upward increase in textural and chemical maturity, with abundant grains (such as feldspar) and some clay minerals derived from the weathered basalt near the base. Towards the top, there is almost no clay in the matrix of the sandstone and the grains consist almost entirely of sub-rounded to sub-angular quartz. Almost all the grains have an iron-oxide coating, covered by a layered carbonate coating. Silica has

filled in the remaining voids. The carbonate and silica are considered to be diagenetic features.

The major influence of the N trending fault on the transport directions into the saline lake at B1 and B2, is evident from the Mmashoro Area map. To the west of this fault, transport was to the west (such as at C), while to the east of the fault, transport was into the saline lake at B1 and B2. This is supporting evidence for fault control on the deposition of Orapa Subgroup sediments.

The trough cross-bedding and basal conglomerate indicate intermediate to fast current velocities. The sediments at profile C are interpreted to have been deposited during flood events in a semi-arid environment. The moderate to poor sorting of the sandstones and the isolated Tigillites trace fossils suggest a fluvial depositional environment.



#### (5.5.5) LSF (Mmashoro Area)

The sandstones of the Mmashoro Formation are typically unconformably overlain by the Letlhakane Stoneline Formation (LSF) south and west of the scarp. At A1, A2 and D the LSF consists almost entirely of clasts of lacustrine chert, with minor Mmashoro Formation sandstone clasts. A few broken pieces of stromatolites were also found in the LSF. This clearly indicates the former existence of a saline lake in this area, as shown also by the presence of Mmashoro Formation sediments with layered chert at B1.

Transport by the braided streams at A1, A2 and D, has therefore been into this saline lake. With time, the lake extended laterally to cover the fluvial sediments at A1, A2 and D as shown also by the *Thalassinoides* trace fossils. The amount of chert in the LSF increases substantially from A1 (30 %) to the vicinity of B1 (90 %). This is probably due to an increase in the thickness of the rhythmites from A1 to B1 that existed prior to the landscape denudation.

The landscape denudation associated with the LSF removed most of the lake sediments so that only the resistant chert remained. Judging from the distribution of the formerly layered, lacustrine cherts in the LSF, the Early Kalahari saline lake must have covered a large area (at least 525 km<sup>2</sup>) in this part of Botswana.

At B1 and B2 the Makoba Subgroup sediments were eroded away by the headwaters of the Moenyenana River (Fig. 3f), but they can still be found on top of the lake sediments, 0,5 km to the south of B1.

The Mmashoro Sandstone Formation is also, a few metres away from the road cut at C, overlain by the LSF and the Gordonia Formation. The (50 cm thick) LSF here consists entirely of sandstone clasts (up to 4 cm long) of the underlying Mmashoro Sandstone. It is ferricreted in this locality, overlying Mmashoro Formation sandstones from here, to the Letlhakane Mine in the Orapa-Letlhakane Area (~ 100 km to the west) and northward to the South Sua Pan Area (also about 100 km). The LSF has not been traced southwards due to the lack of suitable access roads and outcrops.

#### (5.5.6) Debe Calcrete Formation (Mmashoro Area)

But for a few remnants, the Debe calcretes have been completely dissolved. The remaining calcrete consists of hardpan calcrete that has a displacing effect on the LSF clasts.

#### (5.5.7) Gordonia Formation (Mmashoro Area)

The unconsolidated reddish-brown sands of the Gordonia Formation form NE trending dunes in the Mmashoro Area (Fig. 3f). The linear dunes occur in a series of long, parallel ridges, separated from each other by broad interdune areas. The most important factor for linear dune formation, is the presence of strong winds of uniform direction (Reineck and Singh, 1980). The stronger the wind, the larger the linear dunes and the greater the interdune spacing. The linear dunes are now vegetated and degraded. They form part of a large semi-circular arc of dunes, which corresponds to the outblowing pattern of winds around the Southern African anticyclone situated over the northern Transvaal (Grove, 1969, Mallick et al., 1981; Lancaster, 1981 and Deacon and Lancaster, 1988). The winds are therefore thought to have blown from an easterly direction in the study areas.



## (6) SILCRETES IN THE KALAHARI GROUP

Lamplugh (1902) originally coined the terms calcrete and silcrete to describe indurated masses cemented either by calcium carbonate or silica. Langford-Smith (1978) described silcretes as very brittle, hard rocks, composed of clasts cemented by crystallized quartz, cryptocrystalline quartz or amorphous (opaline) silica. Silcretes are the result of cementation or replacement of rocks or sediments by silica so that they finally consist of more than 85% silica.

There is little agreement in the literature about how and under what environmental conditions silcretes form. Watson (1989) is of the opinion that silcretes in the Namib and greater Kalahari may be lacustrine, phreatic or pedogenic. Summerfield (1983) suggested silcrete genesis in alkaline, semi-arid environments for the Kalahari Group.

The silcreted sediments of the Mmashoro Sandstone Formation are mostly of the grain-supported quartzitic types, similar to those described by Summerfield (1983). Locally, bands of silcreted sediments with more than 40% silica cement, up to 20 cm thick, occur in the Mmashoro Sandstone sediments of the study areas. These bands are of Summerfield's (1983) Terazzo types (>5% skeletal grains, floating in a massive siliceous matrix). Silcretes with grain-supported fabrics and some Terazzo types are diagnostic of arid zones (Watson, 1989). Care should be taken not to describe sediments of the Kalahari Group merely as silcretes (i.e. Summerfield, 1983). To avoid the loss of a wealth of information on the Kalahari Group, some sediments should rather be seen as silicified sediments and an attempt should be made to determine the sedimentary characteristics. Trace fossils and cross-bedding is often highlighted by the silicification.

Most silcretes in the Kalahari Group are thought to be of lacustrine origin, due to the saline lake sub-environments in which sediments were deposited under semi-arid climatic conditions. The remainder is interpreted as being diagenetic in origin.

## (7) CALCRETES IN THE KALAHARI GROUP

In general, it can be stated that calcrete is formed near-surface in stable geomorphic areas, where for a certain period of time negligible sediment deposition took place.

Calcium carbonate accumulation in the Makoba Subgroup is thought to be mainly due to pedogenic processes in the Kalahari, involving evaporative precipitation of  $\text{CaCO}_3$ . The main sources of calcium ions are dissolved calcium in rain water, aeolian dust with some carbonate content and/or calcium available within the sediment. Calcretes and accumulations of carbonate in the Early Kalahari sediments, such as in the basal fluvial conglomerates (sections 5.5.2 and 5.5.4) and alluvial fans (section 5.3.1) are considered to be mainly groundwater calcretes as defined by Wright and Tucker (1991). Stable isotope work, which is beyond the scope of this thesis, might shed more light on the pedogenic or phreatic nature of the different Kalahari calcretes. However, there is a whole range of mechanisms causing carbonate precipitation, such as evaporation, evapotranspiration, degassing and microbial activity (Wright and Tucker, 1991), and more work is needed before the links between climate, biology and calcrete morphology can be used for palaeoenvironmental reconstructions. All that can be stated with certainty at present, is that calcretes developed near surface in terrestrial environments with negligible sediment accumulation.

Generally, calcretes consist of: 80%  $\text{CaCO}_3$ ; 12%  $\text{SiO}_2$ ; 3%  $\text{MgO}$ ; 3%  $\text{Fe}_2\text{O}_3$  and 2%  $\text{Al}_2\text{O}_3$  (Goudie, 1983). Calcretes are, however, chemically very variable, due to their diverse origins and different stages of development.

The calcretes in the Kalahari Group are mostly white, but in places grey, cream or pink in colour. They show large variations in the percentages of high-magnesian calcrete and dolomite, related to the presence of sepiolite and palygorskite (Watts, 1980). Sepiolite, palygorskite and montmorillonite were found to be the most common clay minerals in the sediments of the Orapa Subgroup. The presence of palygorskite in the clay fraction is a good indication of alkaline, hypersaline conditions in the depositional basin, whereas montmorillonite is produced mainly in arid and temperate climates (Reineck and Singh, 1980). Sepiolite is a neo-formational clay derived from montmorillonite under alkaline conditions (Du Plessis and Lamos, 1990).

These clay minerals therefore provide additional evidence for the semi-arid climate and alkaline saline conditions in the lakes and related environments of the Orapa Subgroup.

Two distinct regional calcrete horizons were recognized in the study areas, representing periods of non-deposition and sub-aerial exposure (Fig. 6).

The oldest calcrete overlies the 90 Ma kimberlites and surrounding bedrock in the Orapa - Letlhakane Area. This post-Orapa kimberlite - pre-Kalahari calcrete (which also contains some silcrete), was eroded by the Early Kalahari sediments of the Orapa Subgroup. The Mmashoro Sandstone Formation contains abundant clasts of this calcrete (and silcrete) in a basal conglomerate at locality C in the Mmashoro Area.

The next stage of calcretization occurred after the formation of the LSF to form the second, easily recognizable, regional calcrete (Fig. 6). The displacing effect of the calcretization can often be seen in the normally clast-supported LSF, attaining a matrix-supported character. Rill-marks on top of this calcrete and the karst surface that developed indicate the erosive effect of a subsequent wetter period.

## (8) SUMMARY

A model for the depositional history of the different lithologies in the study areas can be summarized as follows:

After the intrusion of the Cretaceous kimberlites at about 90 Ma, epiclastic crater lake sediments were deposited in a relatively short time. Sedimentation often took the form of debris and mud flows under temperate, seasonal and wet climatic conditions in a forested area (Rayner et al., 1991). Between 50 m and 100 m of sediment was subsequently removed by erosion from the A/K 1 kimberlite pipe at Orapa (Rayner et al., 1991).

The low energy, distal, lacustrine Mmashoro Formation sediments (section 5.2.1) contradict the occurrence of strong erosion in Early Kalahari times in the vicinity of the Orapa kimberlite (A/K 1). A great deal of the erosion must therefore have occurred prior to Kalahari deposition. This supports the notion that deep weathering and erosion took place in the post-kimberlite - pre-Kalahari period. This deep weathering is also seen in the boreholes drilled into the Drakensberg basalt that show weathered basalt down to 15 metres from the upper basaltic contact.

This period of deep weathering was terminated with the deposition of a hardpan calcrete that caps both the Drakensberg basalt and the kimberlites in the study areas. This calcrete was eroded by currents depositing the Early Kalahari sediments.

Although seasonal, wet climatic conditions reigned at about 90 Ma, the Cretaceous is interpreted to have become sufficiently dry for conditions to have been semi-arid during the deposition of Early Kalahari sediments. The Kwari Formation (unconformably overlain by the Kalahari Group) may already have been deposited under semi-arid conditions.

The next major event was the proposed tectonic event (possibly in the Late Cretaceous at about 70 Ma) that broke southern Africa up into horsts and grabens. Major depositional basins formed as a result, each with its floor broken up into horsts and grabens. With the prevailing semi-arid climate, frequent flash floods, coupled with abundant unconsolidated sand (produced during the long period of deep weathering in the Cretaceous) fairly rapidly filled in the grabens. Thorough erosion of the horsts also took place. Graben in-filling first took the form of fluvial sedimentation, followed by lacustrine sedimentation as the grabens were in-filled and the landscape was planated, resulting in lower and lower depositional energy. This basin in-filling was probably completed in the early part of the Tertiary. This was in turn followed by a long period of non-deposition, weathering and erosion in the Tertiary that lowered the landscape by more than 25 metres in the Orapa area

resulting in a lag deposit, the Letlhakane Stoneline Formation (LSF). This lag formation was possibly completed by the Miocene.

The deposition of the LSF was followed by the deposition of regional calcretes, which are superimposed in the study areas and have a possible range in age from the Miocene to the very late Pleistocene. In the early part of the Holocene, very arid conditions resulted in the formation of vast linear dune systems in southern Africa. Subsequent wetter climatic conditions in the Holocene caused the degradation, bioturbation and vegetation of the dunes.

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# (10) REFERENCES

- Adams, A.E., MacKenzie, W.S. and Guilford, C. (1991). *Atlas of Sedimentary Rocks under the Microscope*. Longman, New York, 104 pp.
- Baillieul, T.A. (1975). A reconnaissance survey of the cover sands in the Republic of Botswana. *J. Sed. Petr.*, **45**(2), 494-503.
- (1979). The Makgadikgadi pans complex of central Botswana. *Bull. Geol. Soc. Am.*, **90**, 133-136.
- Binda, P.L. and Hildred, P.R. (1973). Bimodal grain-size distributions of some Kalahari sands from Zambia. *Sed. Geol.*, **10**, 233-237.
- Bond, G. (1948). The direction of origin of the Kalahari Sand of Southern Rhodesia. *Geol. Mag.*, **85**, 305-313.
- Boocock, C. and Van Straten, O.J. (1962). Notes on the geology and hydrogeology of the Central Kalahari region, Bechuanaland protectorate. *Trans. Geol. Soc. S. Afr.*, **65**, 125-171.
- Brook, G.A., Burney, D.A. and Cowary, J.B. (1990). Desert palaeoenvironmental data from cave speleothems with examples from the Chihauhaun-, Somali-Chalbi- and Kalahari deserts. *Palaeogeogr., Palaeoclimatol., Palaeoecol.*, **76**, 311-329.
- Brown, R.W. (1990). *Apatite Fission Track Analysis (AFTA) Results from the Kaap Vaal Craton and Hydrocarbon Exploration Drill Hole Swartberg 1/67*. De Beers report (unpubl.).
- Bruno, S.A. (1985). Pan genesis in the southern Kalahari. In: Hutchins, D.G. and Lynam, A.P. (Eds.), *The Proceedings of a Seminar on the Mineral Exploration of the Kalahari*, *Bots. Geol. Surv., Bull.*, **29**, 261-277.
- Buckley, R. (1981). Parallel dunefield ecosystems - southern Kalahari and central Australia. *J. Arid Env.*, **4**, 287-298.
- Butzer, K.W. (1984). Late Quaternary environments in South Africa. In: Vogel, J.C. (Ed.), *Late Cainozoic Palaeoclimates of the Southern Hemisphere*, Balkema, Rotterdam, 235-264.



- Butzer, K., Stuckenrath, R., Bruzewicz, A. and Helgren, D. (1978). Late cenozoic palaeoclimates of the Ghaap Escarpment, Kalahari Margin, South Africa. *Quat. Res.*, **10**, 310-339.
- Cahen, L. and Lepersonne, J. (1952). Equivalence entre le systeme du Kalahari du Congo Belge et les Kalahari Beds d'Afrique Australe. *Mem. Soc. Belg. Geol.*, **8**, 1-64.
- Cahen, D. and Moeyersons, J. (1977). Subsurface movements of stone artefacts and their implications for the prehistory of Central Africa. *Nature*, **266** (5605), 812-815.
- Coates, J.N.M., Davies, J., Gould, D., Hutchins, D.G., Jones, C.R., Key, R.M., Massey, N.W.D., Reeves, C.V., Stansfield, G. and Walker, I.R. (1979). *The Kalatraverse One Report*, Dir. Geol. Surv., Lobatse, Botswana.
- Cooke, H.J. (1975a). The palaeoclimatic significance of caves and adjacent landforms in the Kalahari of western Ngamiland, Botswana. *Geogr. J.*, **143**, 431-444.
- (1975b). The Lobatse Caves. *Bots. Notes and Rec.*, **7**, 29-33.
- (1979). Radiocarbon chronology of Late Quaternary lakes in the Kalahari, Southern Africa: a discussion. *Catena*, **6**, 107.
- (1984). The evidence from northern Botswana of climatic change. In: Vogel, J. (Ed.), *Late Cenozoic Palaeoclimates of the Southern Hemisphere*. Balkema, Rotterdam, 520 pp.
- and Verhagen, B.T. (1977). The dating of cave development - an example from Botswana. *Proc. 7th Int. Congr. Speleol.*, Sheffield, 122-124.
- and Verstappen, H.T. (1984). The landforms of the western Makgadikgadi basin in northern Botswana, with a consideration of the chronology of the evolution of Lake Palaeo-Makgadikgadi. *Z. Geomorph. N.F.*, **28**, 1-19.
- Deacon, J. and Lancaster, N. (1988). *Late Quaternary Palaeoenvironments of Southern Africa*. Oxford University Press, New York, 209 pp.
- Dunham, R.J. (1962). Classification of carbonate rocks according to depositional texture. In: Ham, W.E. (Ed.), *Classification of Carbonate Rocks*. Am. Assoc. Petrol. Geol., Mem. **1**, 108-121.

- Du Plessis, P.I. (1990). *Palaeodrainage of Botswana*. De Beers report (unpubl.), 20 pp.
- and Lamos, R.A. (1990). *Progress Report on the Kalahari Sediments in the Northwestern Transvaal*. Soil Science Dept. (unpubl.), Potchefstroom Univ., Potchefstroom, 80 pp.
- Du Toit, A.L. (1954). *Geology of South Africa*. Oliver and Boyd, Edinburgh, 611 pp.
- Ebert, J.I. and Hitchcock, R.K. (1978). Ancient Lake Makgadikgadi, Botswana: mapping, measurement and palaeoclimatic significance. *Palaeoecol. Afr.*, 10/11, 47-56.
- Eriksson, P.G., Nixon, N., Snyman, C.P. and Bothma, J. du P. (1989). Ellipsoidal parabolic dune patches in the southern Kalahari Desert. *J. Arid Environ.*, 16, 111-124.
- Fisher, R.V. (1971). Features of coarse-grained, high concentration fluids and their deposits. *J. Sed. Petr.*, 41, 916-927.
- Flint, R.F. and Bond, G. (1968). Pleistocene sand ridges and pans in western Rhodesia. *Bull. Geol. Soc. Am.*, 79, 299-314.
- Folk, R.L. (1974). *Petrology of sedimentary rocks*. Hemphills, Austin, Texas, 474 pp.
- Frey, R.W. (1975). *The Study of Trace Fossils*. Springer Verlag, New York, 562 pp.
- Goudie, A.S. (1970). Notes on some major dune types in southern Africa. *S. Afr. Geogr. J.*, 52, 93-101.
- (1983). Calcrete. In: Goudie, A.S. and Pye, K. (Eds.) *Chemical Sediments and Geomorphology*. Academic Press, London. 93-132.
- and Thomas, D.S.G. (1985). Pans in southern Africa with particular reference to South Africa and Zimbabwe. *Zeitschr. für Geomorph.*, 29, 1-19.
- and Thomas, D.S.G. (1986). Lunette dunes in southern Africa. *J. Arid Environ.*, 10, 1-12.
- Grey, D.R.C. (1976). "The prospecting of the Mopipi area." Anglo-American Corp. report (unpubl.), 97 pp.
- and Cooke, H.J. (1977). Some problems in the Quaternary evolution of the landforms of northern Botswana. *Catena*, 4, 123-133.
- Grove, A.T. (1969). Landforms and climatic change in the Kalahari and Ngamiland. *Geogr. J.*, 135, 191-212.

- Halliwell, G. (1987). *The stratigraphy of the Kalahari Formation in Southern Africa*. De Beers report (unpubl.), 20 pp.
- Häntzschel, W. (1962). Trace fossils and problematica. In: Moore, R.C. (Ed.), *Treatise on Invertebrate Paleontology*. Kansas Geol. Soc., Univ. Kansas Press, 177-245.
- Hardie, L.A., Smoot, J.P. and Eugster, H.P. (1978). Saline lakes and their deposits: a sedimentological approach. In: Matter, A. and Tucker, M.E. (Eds.), *Modern and Ancient Lake Sediments*. Spec. Publ. Int. Ass. Sediment., 2, 7-14.
- Haughton, S.H. (1963). *The Stratigraphic History of Africa South of the Sahara*. Oliver and Boyd, Edinburgh, 365 pp.
- Heine, K. (1978a). Radiocarbon chronology of Late Quaternary lakes in the Kalahari, Southern Africa. *Catena*, 5, 145-149.
- (1978b). Jungquartäre pluviale und interpluviale in der Kalahari (Südliches Afrika). *Palaeoecol. Afr.*, 10, 31-39.
- (1982). The main stages of the late Quaternary evolution of the Kalahari region, southern Africa. *Palaeoecol. Afr.*, 15, 53-76.
- Helgren, D.M. (1978). Environmental history in the northwest Kalahari - a preliminary report. *Palaeoecol. Afr.*, 10, 65-66.
- (1984). Historical geomorphology and geoarchaeology in the south-western Makgadikgadi basin, Botswana. *Ann. Assoc. Amer. Geogr.*, 74, 298-307.
- Hövermann, J. (1988). The Sahara, Kalahari and Namib Deserts: A geomorphological comparison. In: Dardis, G.F. and Moon, B.P. (Eds.), *Geomorphological Studies in Southern Africa*, Balkema, Rotterdam, 71-83.
- Lamplugh, G.W. (1902). "Calcrete". *Geol. Mag.*, 9, 575 pp.

Lancaster, N. (1978). The pans of the southern Kalahari, Botswana. *Geogr. J.*, **144**, 81-98.

---- (1979). Evidence for a widespread late Pleistocene period in the Kalahari. *Nature*, **279**, 145-146.

---- (1980). Dune systems and palaeoenvironments in southern Africa. *Palaeoent. Africana.*, **23**, 185-189.

---- (1981). Palaeoenvironmental implications of fixed dune systems in Southern Africa. *Palaeogeogr., Palaeoclimatol., Palaeoecol.*, **33**, 327-346.

---- (1986a). Grain-size characteristics of linear dunes in the south-western Kalahari. *J. Sed. Petr.*, **56**, 395-400.

---- (1986b). Pans in the south-western Kalahari: a preliminary report. *Palaeoecol. Afr.*, **17**, 59-67.

---- (1987a). Formation and reactivation of dunes in the southwestern Kalahari: Palaeoclimatic implications. In: Coetzee, J. A. (Ed.), *Palaeoecology of Africa and the Surrounding Islands*. Balkema, London, **18**, 103-110.

---- (1987b). Grain-size characteristics of linear dunes in the south-western Kalahari - a reply. *J. Sed. Petr.*, **57**, 573-574.

---- (1988). Development of linear dunes in the southwestern Kalahari, southern Africa. *J. Arid Environ.*, **14**, 233-244.

---- (1989). Late Quaternary palaeoenvironments of the southwestern Kalahari. *Palaeogeogr., Palaeoclimatol., Palaeoecol.*, **70**, 367-376.

Langford-Smith, T. (1978). A selected review of silcrete research in Australia. In: Langford-Smith, T. (Ed.), *Silcrete in Australia*. Department of Geography, University of New England, Armidale, NSW, 1-11.

Le Roux, J.P. and Rust, I.C. (1989). Composite facies maps: a new aid to palaeo-environmental reconstruction. *S. Afr. J. Geol.*, **92**(4), 436-443.

Lister, L.A. (1979). The geomorphic evolution of Zimbabwe-Rhodesia. *Trans. Geol. Soc. S. Afr.*, **82**, 363-370.

Mabbutt, J.A. (1955). Erosion surfaces in Namaqualand and the ages of surface deposits in the south-western Kalahari. *Trans. Geol. Soc. S. Afr.*, **58**, 13-29.

Malherbe, S.J., Keyser, A.W., Botha, B.J.V., Cornelissen, A., Slabbert, M.J. and Prinsloo, M.C. (1986). The Tertiary Koa River and the development of the Orange River Drainage. *Ann. Geol. Surv. S. Afr.*, **20**, 13-23.

Mallick, D.I.J., Habgood, F. and Skinner, A.C. (1981). A geological interpretation of Landsat imagery and air photography of Botswana. *Overs. Geol. Min. Res.*, **56**, 1-35.

Maupe, H.B. (1920). The geological section between Bulawayo and Victoria Falls, Rhodesia. *S. Afr. J. Sci.*, **17**, 113-115.

---- (1939). New sections in the Kalahari beds at the Victoria Falls, Rhodesia. *Trans. Geol. Soc. S. Afr.*, **31**, 211-224.

Moeyersons, J. (1978). The behaviour of stones and stone implements, buried in consolidating and creeping Kalahari sands. *Earth Surface Processes*, **3**, 115-128.

Money, N.J. (1972). An outline of the geology of western Zambia. *Rec. Geol. Zambia*, **12**, 103-123.

Nemec, W. and Steel, R.J. (1984). Alluvial and coastal conglomerates and their significant features and some comments on gravelly mass-flow deposits. In: Koster, E.H. and Steel, R.J. (Eds.), *Sedimentology of Conglomerates and Gravels*, *Can. Soc. of Petrol. Geol., Memoir 10*, 1-31.

Netterburg, F. (1978). Dating and correlation of calcretes and other pedocretes. *Trans. Geol. Soc. S. Afr.*, **81**, 379-391.

---- (1980). Geology of Southern African calcretes: 1. Terminology, description, macrofeatures and classification. *Trans. Geol. Soc. S. Afr.*, **83**, 255-283.

Passarge, S. (1904). *Die Kalahari*. Reimer, Berlin, 822 pp.

Pickford, M. and Mein, P. (1988). The discovery of fossiliferous Plio-Pleistocene cave fillings in Ngamiland, Botswana. *CR Academie Science Paris, Series 2*, **307**, 1681-1686.

Poldervaart, A. (1957). Kalahari sands. In: Clark, J.D. (Ed.), *The 3rd Pan-African Congress on Prehistory, Livingstone 1955*, Chatto and Windus, London, 106-119.

Rayner, R.J., Waters, S.B., McKay, I.J., Dobbs, P.N. and Shaw, A.L. (1991). The mid-Cretaceous palaeoenvironment of central Southern Africa (Orapa, Botswana). *Palaeogeogr., Palaeoclimatol., Palaeoecol.*, **88**, 147-156.

Reeves, C.V. (1972). Rifting in the Kalahari? *Nature*, **237**, 95-96.

---- and Hutchins, D.G. (1975). Crustal structures in central southern Africa. *Nature*, **273**, 222.

Reineck, H.E. and Singh, I.B. (1980). *Depositional Sedimentary Environments with Reference to Terrigenous Clastics*. Springer Verlag, New York, 549 pp.

- Riccardo, L.A.M. and Christopher, G. (1977). Nature, origin and classification of peritidal tepee structures and related breccias. *Sedimentology*, **24**, 153-210.
- Rogers, A.W. (1936). The surface geology of the Kalahari. *Trans. Geol. Soc. S. Afr.*, **24**, 57-80.
- Rust, U. (1984). Geomorphic evidence of Quaternary environmental changes in Etosha, South West Africa/Namibia. In: Vogel, J. (Ed.), *Late Cainozoic Palaeoclimates of the Southern Hemisphere*. Balkema, Rotterdam, 279-286.
- SACS (1980). South African Committee for Stratigraphy. Stratigraphy of South Africa. Part 1 (Comp. L.E. Kent). *Lithostratigraphy of the Republic of South Africa, South West Africa/Namibia and the republics of Bophuthatswana, Transkei and Venda*. Handbk. geol. Surv. S. Afr., **8**, 690 pp.
- Savat, J. and Poesen, J. (1977). Splash and discontinuous runoff as creators of fine sandy lag deposits with Kalahari sands. *Catena*, **4**, 321-332.
- Shaw, P.A. (1985). Late Quaternary landforms and environmental change in northwest Botswana: the evidence of Lake Ngami and the Mababe Depression. *Trans. Inst. British Geographers.*, **NS 10**, 333-346.
- (1988). After the flood: the fluvio-lacustrine landforms of northern Botswana. *Earth Sci. Rev.*, **25**, 449-456.
- and Cooke, H.J. (1986). Geomorphic evidence for the late Quaternary palaeoclimates of the middle Kalahari of northern Botswana. *Catena*, **13**, 349-359.
- , Cooke, H.J. and Thomas, D.S.G. (1988). Recent advances in the study of Quaternary landforms in Botswana. *Palaeoecol. Afr.*, **19**, 15-26.
- and De Vries, J.J. (1988). Duricrust, groundwater and valley development in the Kalahari of southeast Botswana. *J. Arid Env.*, **14**, 245-254.
- and Thomas, D.S.G. (1989). Pans, playas and salt lakes. In: Thomas, D.S.G. (Ed.), *Arid Zone Geomorphology*, Belhaven Press, London, 184-205.
- Smit, P.J. (1977). *Die geohidrologie in die opvanggebied van die Moloporivier in die noordelike Kalahari*. Unpubl. PhD. thesis, Univ. Orange Free State, Bloemfontein.
- Smith, R.A. (1984). The Lithostratigraphy of the Karoo Supergroup in Botswana. *Bots. Geol. Surv., Bull.* **26**, 239 pp.

Stansfield, G. (1973). The Geology of the Area around Dukwe and Tlalamabele, Central District, Botswana. *Geol. Surv. Botswana, District Mem.*, 1, 73 pp.

Summerfield, M.A. (1982). Distribution, nature and probable genesis of silcrete in arid and semi-arid southern Africa. In: Yaalon, D.H. (Ed.) *Aridic Soils and Geomorphic Processes. Catena Supplement*, 1, 37-65.

---- (1983). Silcrete. In: Goudie, A.S. and Pye K. (Eds.), *Chemical Sediments and Geomorphology*. Academic press, London, 59-91.

Thomas, D.S.G. (1987). Discrimination of depositional environments, using sedimentary characteristics, in the Mega Kalahari, central southern Africa. In: Frostick, L.E. and Reid, I. (Eds.) *Desert Sediments, Ancient and Modern*. Geol. Soc. Lond. Spec. Publ., 35, Blackwell Scientific Publications, Oxford, 293-306.

---- (1988). The nature and depositional setting of arid to semi-arid Kalahari sediments, southern Africa. *J. Arid Env.*, 14, 17-26.

---- (1989). *Arid Zone Geomorphology*. Belhaven Press, London, 372 pp.

---- and Martin, H.E. (1987). Grain-size characteristics of linear dunes in the southwestern Kalahari - discussion. *J. Sed. Petr.*, 57, 231-242.

---- and Shaw, P.A. (1988). Late Cainozoic drainage evolution in the Zambezi Basin: Geomorphological evidence from the Kalahari rim. *J. Afr. Earth Sci.*, 7, 611-618.

---- and ---- (1991). *The Kalahari Environment*. Cambridge University Press, Cambridge, 251 pp.

Thomas, M.A. (1981). *The Geology of the Kalahari in the Northern Cape Province (areas 2620 and 2720)*. Unpubl. MSc. thesis, Univ. Orange Free State, Bloemfontein.

Tyson, P.D. (1986). *Climatic Change and Variability in Southern Africa*. Oxford University Press, 220 pp.



- Unternehrr, P., Curie, D., Olivet, J.L., Goslin, J. and Beuzart, P. (1988). South Atlantic fits and intraplate boundaries in Africa and South America. *Tectonophysics*, 155, 169-179.
- Van Zinderen Bakker, E.M. (1980). Comparison of Late Quaternary climatic evolutions in the Sahara and Namib-Kalahari region. *Palaeoecol. Afr.*, 12, 381-394.
- Watson, A.W. (1989). Desert crusts and rock varnish. In: Thomas, D.S.G. (Ed.), *Arid Zone Geomorphology*, Belhaven Press, London, 25-55.
- Watts, N.L. (1980). Quaternary pedogenic calcretes from the Kalahari (Southern Africa): mineralogy, genesis and diagenesis. *Sedimentology*, 27, 661-686.
- Wells, N.A., Andriamihaja, B. and Rakotovololona, H.F.S. (1990). Stonelines and landscape development on the laterized craton of Madagascar. *Geol. Soc. Am. Bull.*, 102, 615-627.
- Wright, V.P. and Tucker, M.E. (1991). *Calcretes*. Blackwell Scientific Publications, Oxford, 352 pp.

(11) TABLES

Table 1

THE MEAN PEBBLE SIZE (OF THE TEN LARGEST CLASTS AT EACH SAMPLE SITE) AND THE BED THICKNESS OF THE LETLIHAKANE STONELINE FORMATION AROUND 2125 D/K1 AND 2125 D/K2

Sample	Mean pebble size (MPS) in cm	Bed thickness (BTH) in cm
2	2.51	12
3	1.70	8
4	2.57	20
5	3.55	65
6	3.62	118
7	4.16	88
8	4.68	76
9	4.37	105
10	3.62	47
11	3.29	75
D1	3.08	105
D2	3.12	103
D	3.00	50
E	2.75	40
A	5.75	88
B	4.88	80
C	4.59	70

STATISTICS:Regression output:

Constant	2.381520
Std. Err. of Y Est.	0.859262
R. Squared	0.350915
No. of Observations	17
Degrees of Freedom	15
X Coefficient(s)	0.018102
Std. Err. of Coef.	0.006356

**Table 2** THE MEAN PEBBLE SIZE (OF THE TEN LARGEST CLASTS AT EACH SAMPLE SITE) AND THE CLAST COMPOSITION OF THE LETLHAKANE STONELINE FORMATION AT BORROW-PITS 10 TO 14.

Borrow-pits:

14	13	12	11	10
----	----	----	----	----

Average of ten largest clasts in cm:

4.51	2.77	2.40	3.65	5.07
------	------	------	------	------

Clast composition:

95% Bslt. 4% Nt. 1% Mkbl.	90% Bslt. 9% Nt. 1% Mkbl.	50% Bslt. 49% Nt. 1% Mkbl.	4% Bslt. 95% Nt. 1% Mkbl.	0% Bslt. 100% Nt. 0% Mkbl.
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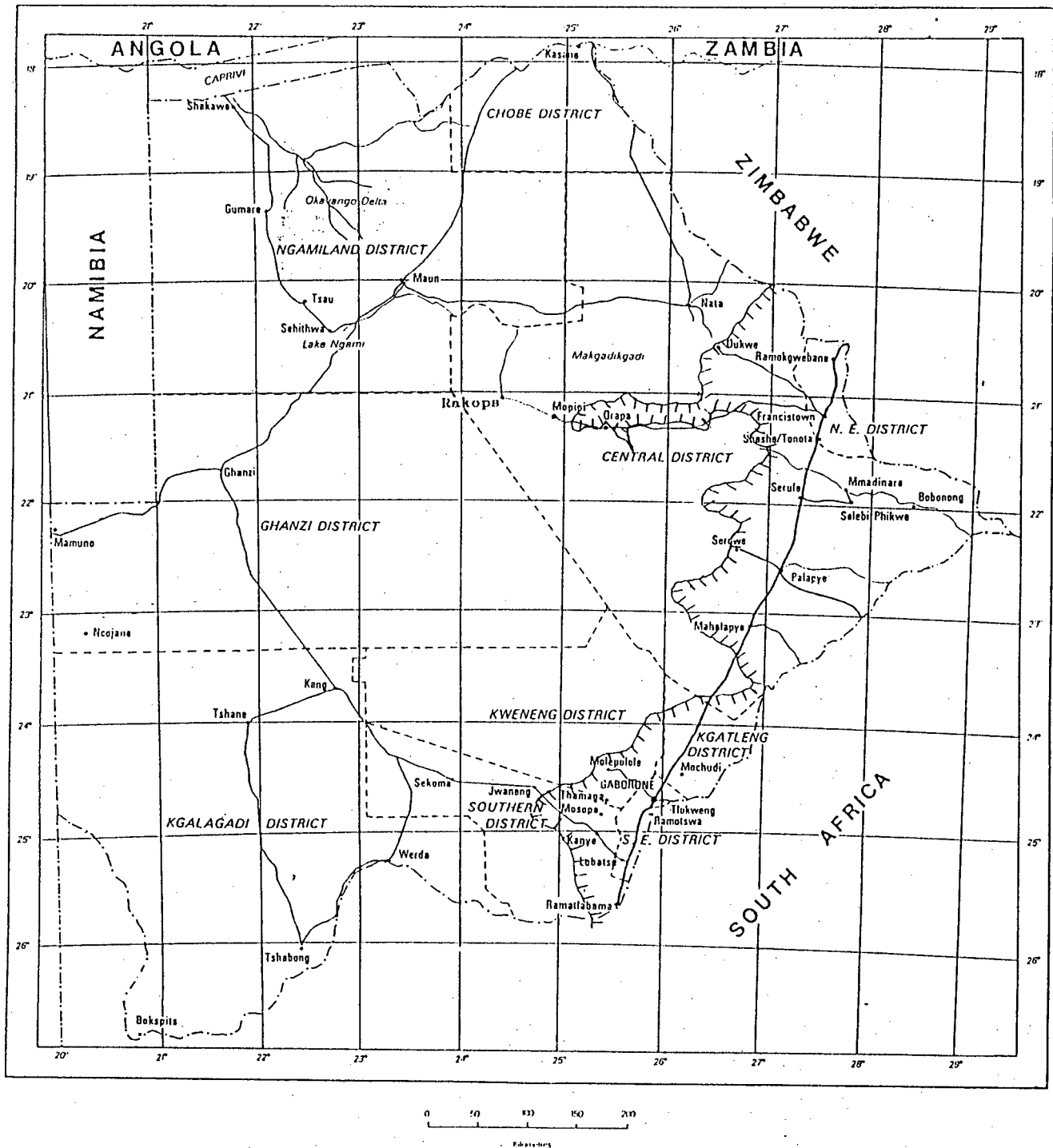
LEGEND

Bslt. = Clasts derived from the Drakensberg basalt  
 Nt. = Clasts derived from the Ntane Formation  
 Mkbl. = Clasts derived from the Mmashoro Formation

Measurements were made in a 50x50 cm grid at each locality.

(12) FIGURES

REPUBLIC OF BOTSWANA



**Eastern limit of Early Kalahari sediments**

**Fig. 1**

## Location of study areas in Botswana

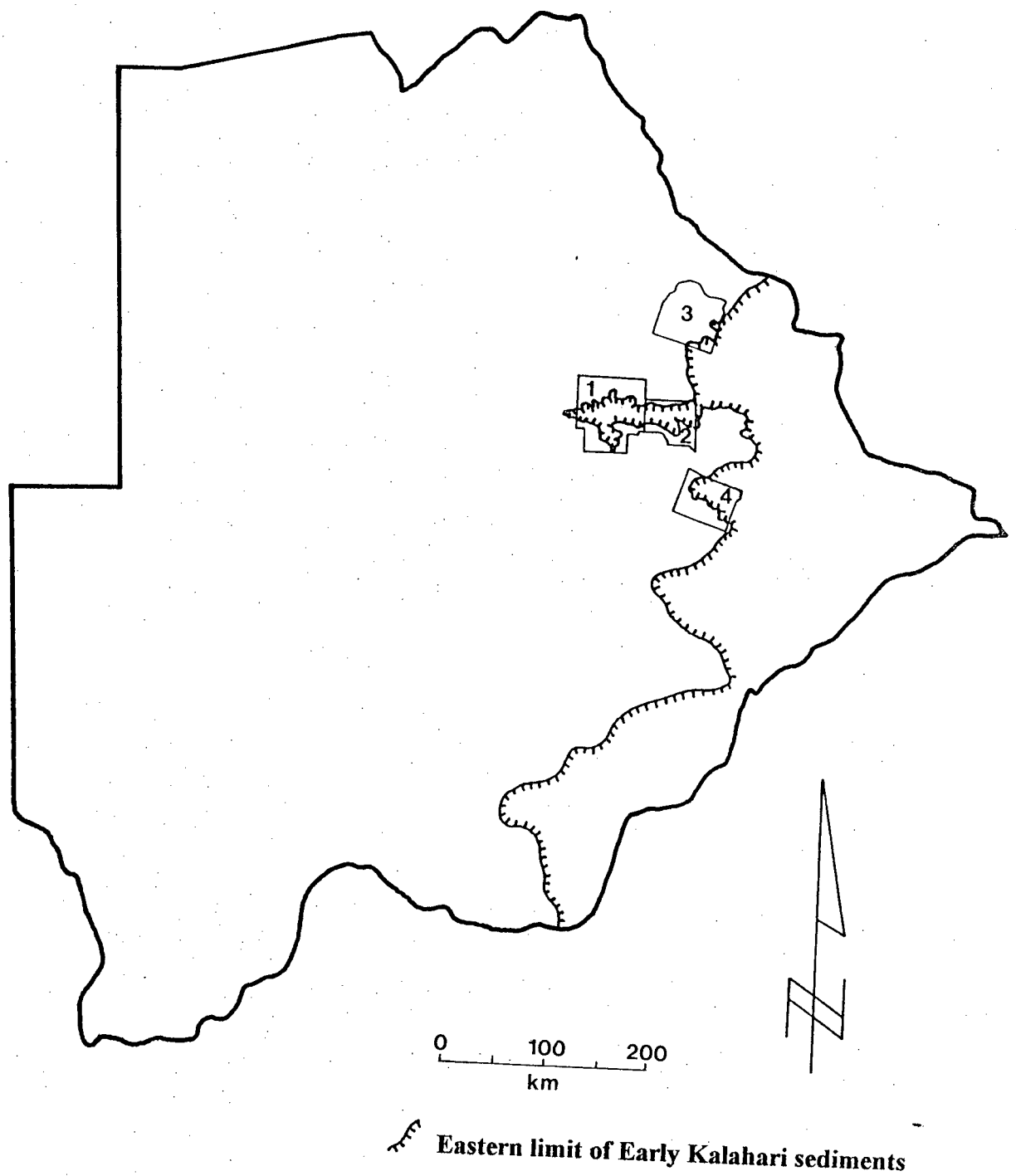


Fig. 2



Fig. 3a

# GEOGRAPHIC LOCATION OF STUDY AREAS

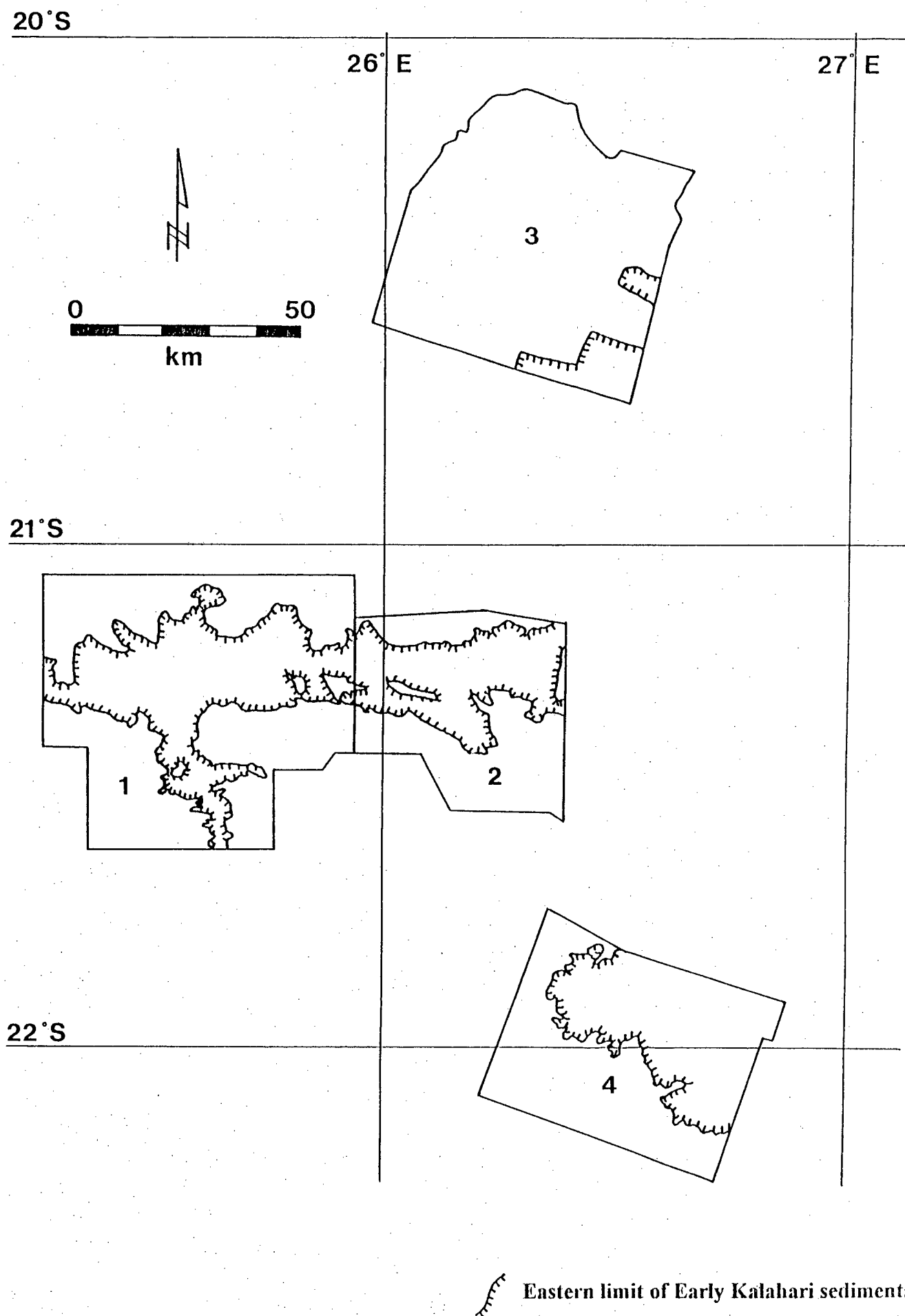
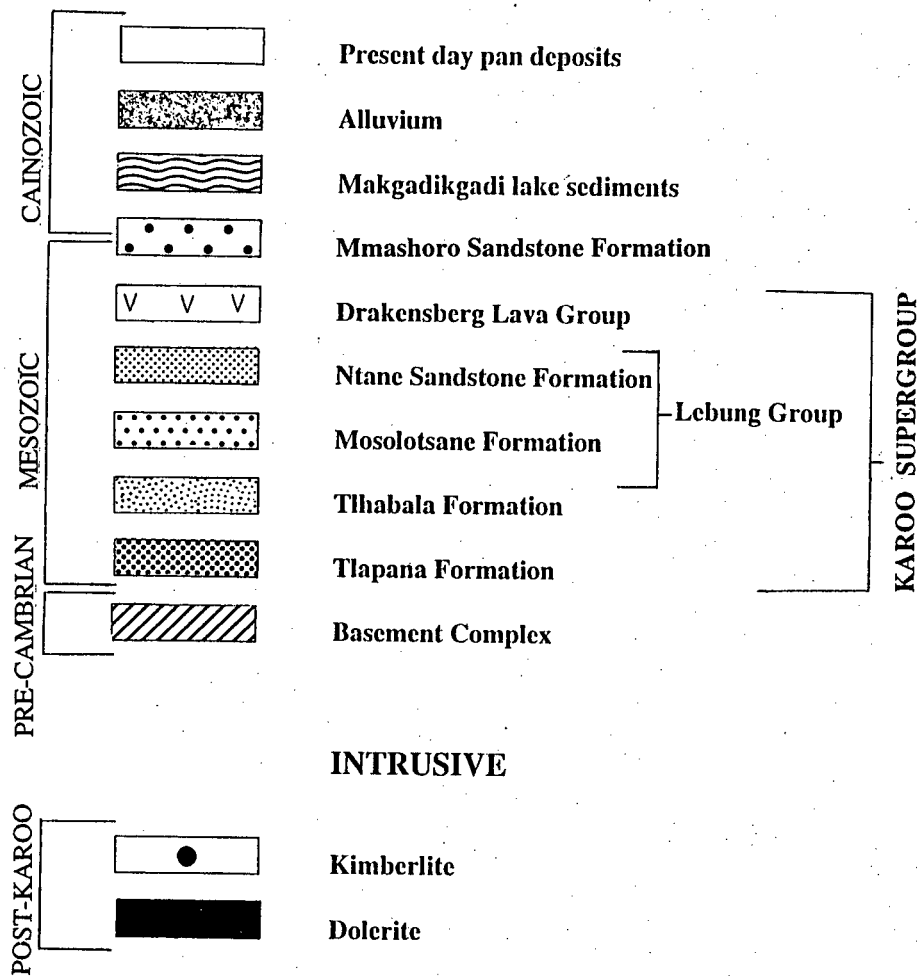


Fig. 3b

## GEOLOGICAL LEGEND OF STUDY AREAS 1 TO 4



### INTRUSIVE

Kimberlite  
Dolerite

### GEOLOGICAL SYMBOLS

- A Sample site
- ..... Dune crests
- ▲▲▲ Strandline (beach ridge)
- ▲▲▲ Scarp
- ▲▲▲ Fault, tick on downthrow side
- Dolerite dyke
- ▲ Palaeocurrent direction
- Kimberlite position
- X AK1 Mined kimberlite
- ☁ Palaeopan

### TOPOGRAPHICAL SYMBOLS

- == Road
- Settlement
- ~ Watercourses

STUDY AREA 1

ORAPA – LETLHAKANE AREA

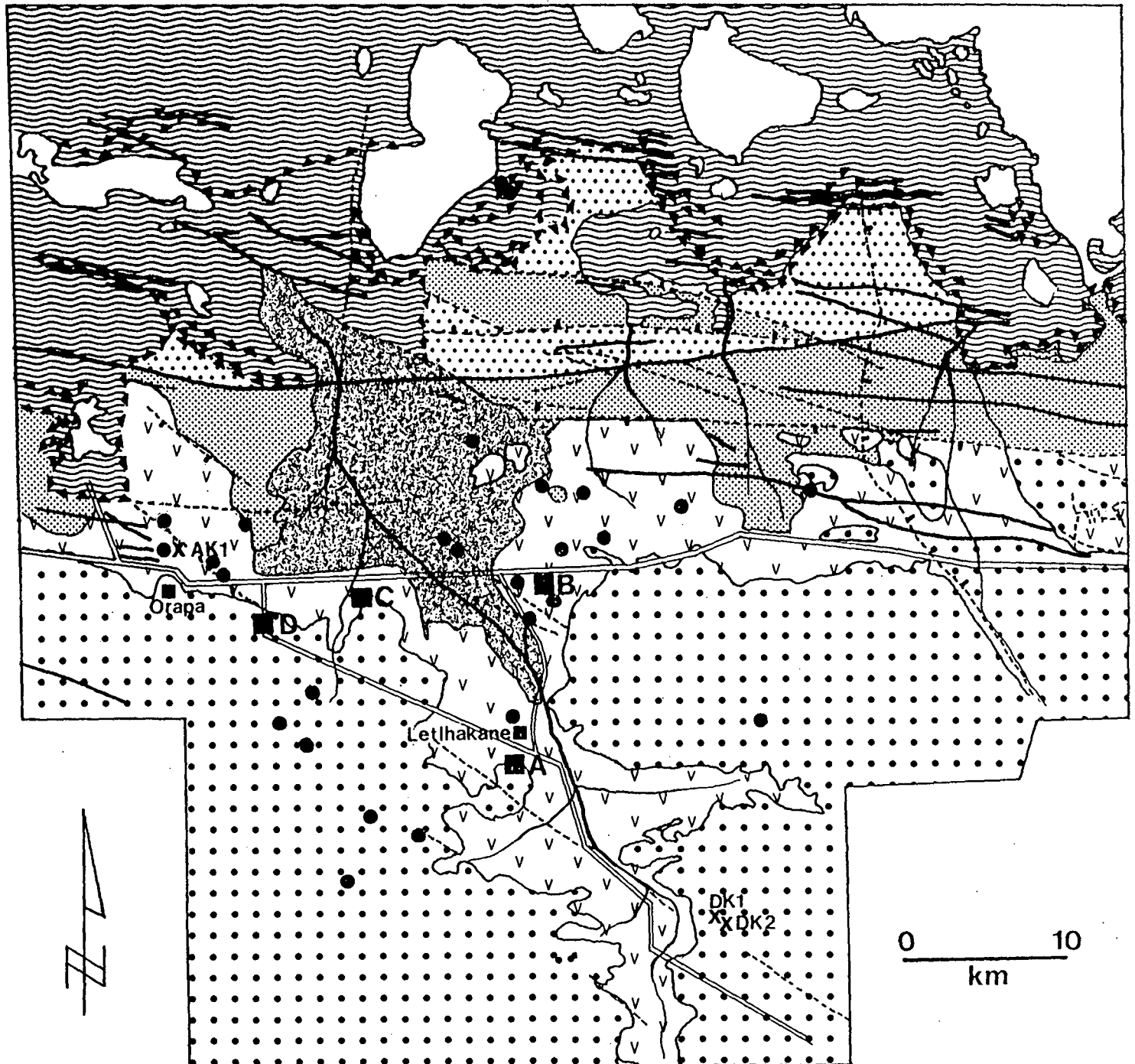


Fig. 3c

STUDY AREA 2  
SOUTH SUA PAN AREA

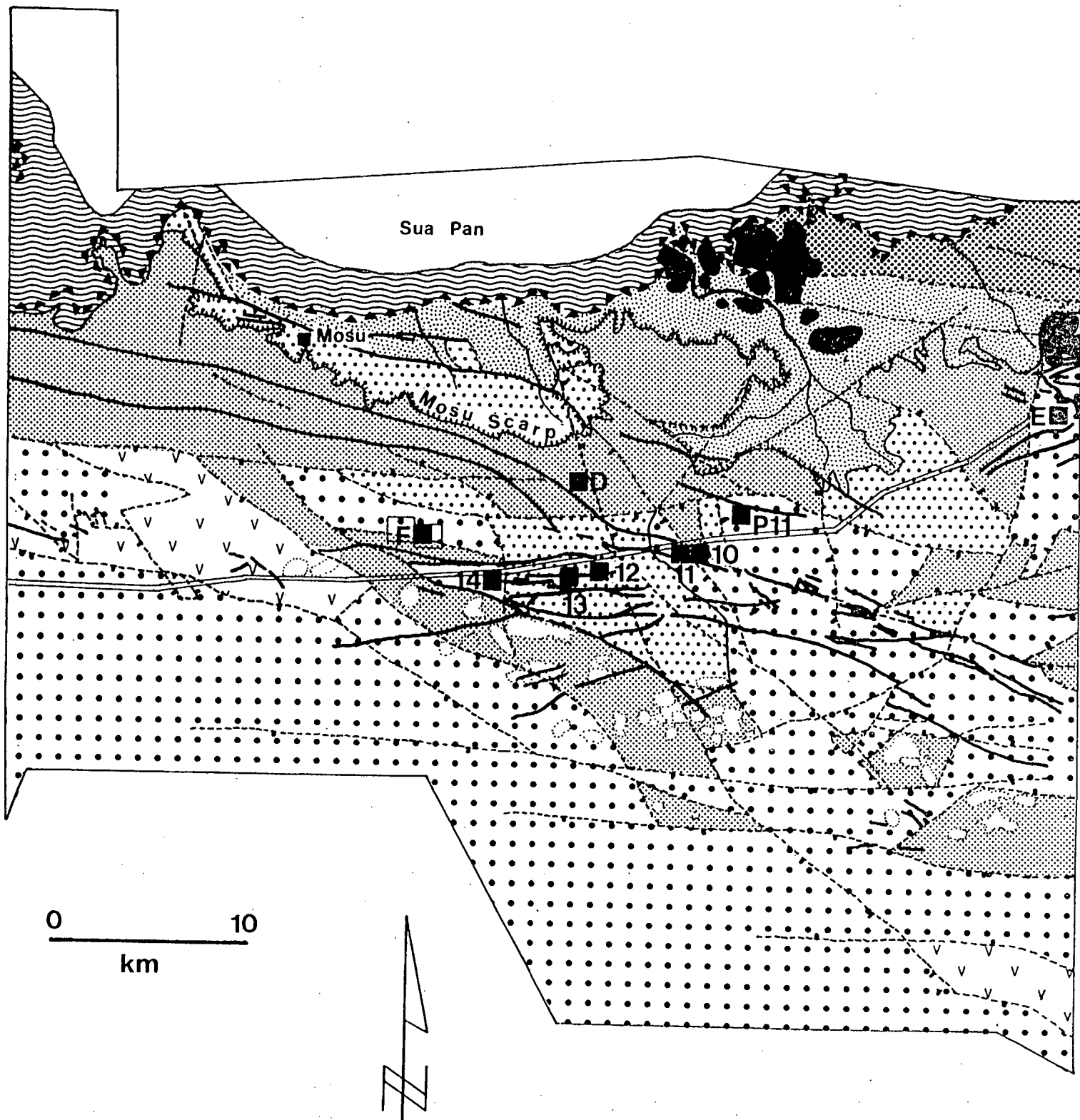


Fig.3d

**STUDY AREA 3**  
**NATA AREA**

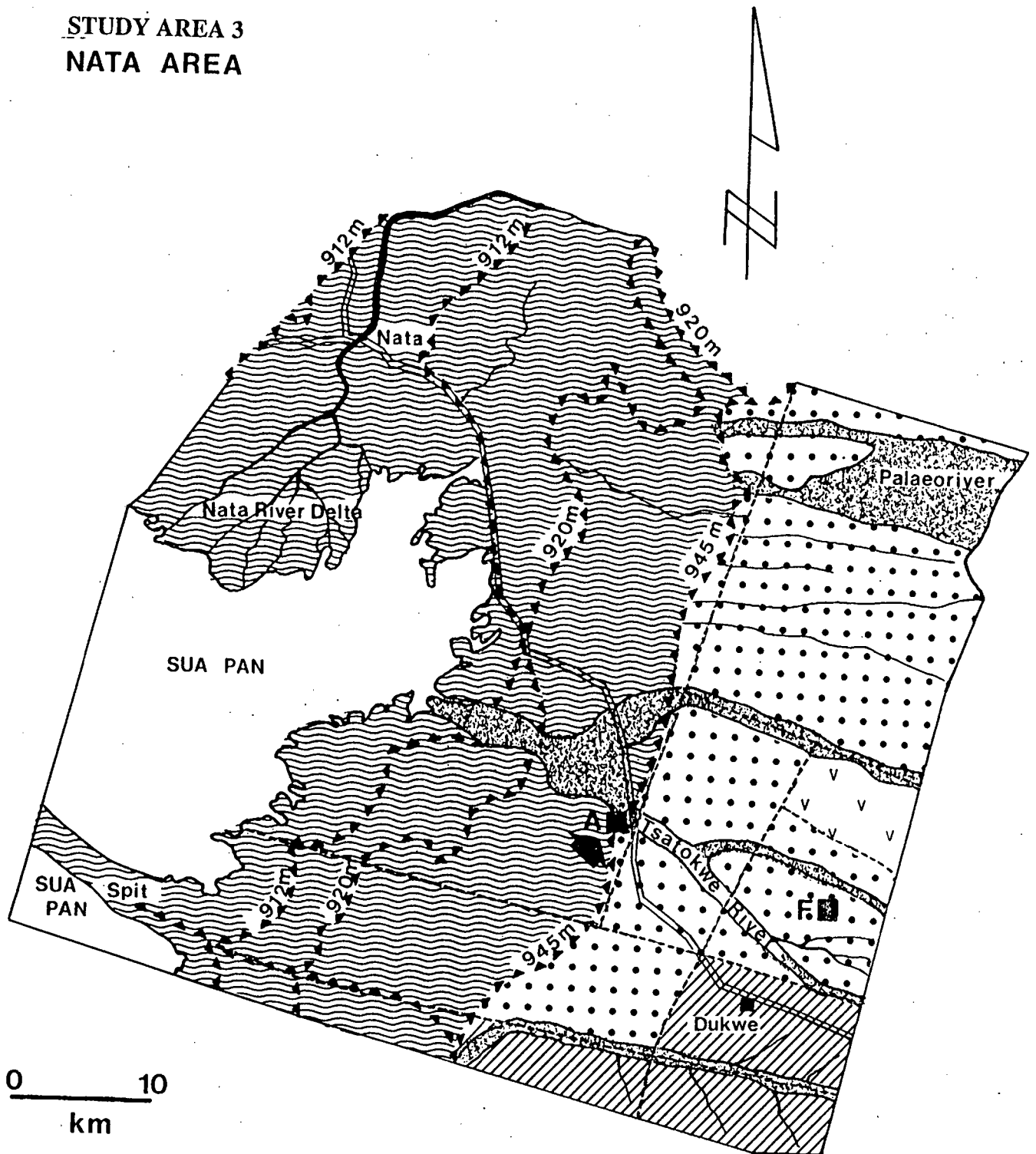


Fig.3e

**STUDY AREA 4**  
**MMASHORO AREA**

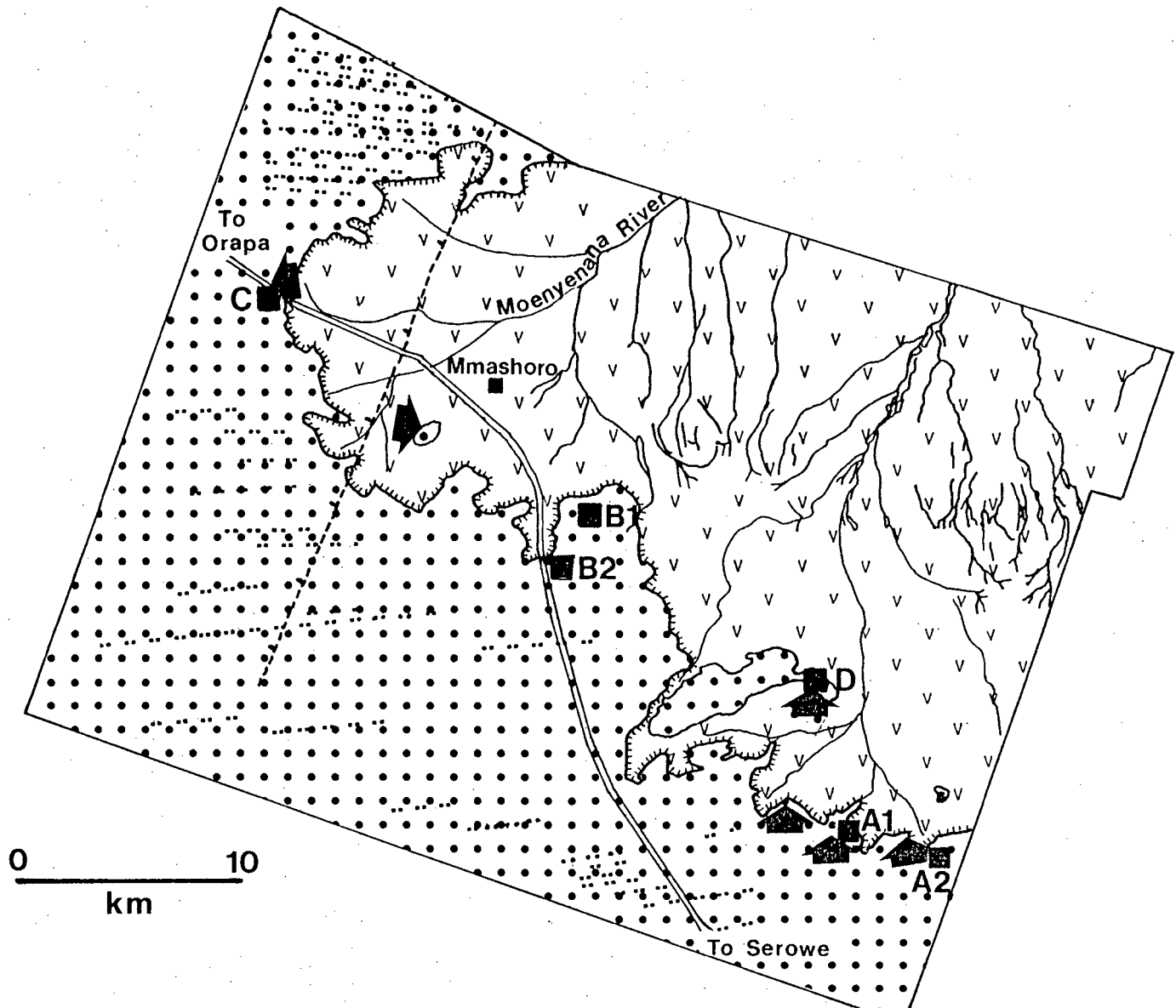
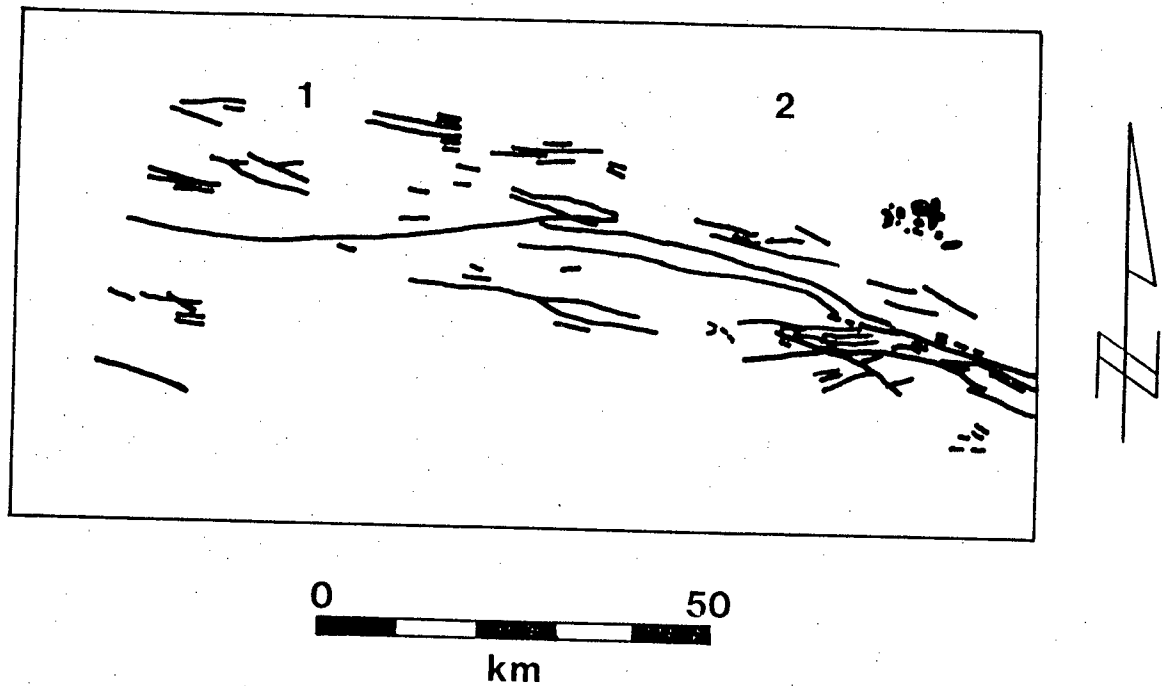


Fig.3f

**POST-KAROO DOLERITE DYKE ORIENTATION IN THE  
ORAPA-SOUTH SUA PAN AREA (STUDY AREAS 1 AND 2)**



**Fig. 4**



## FAULTS IN THE ORAPA-SOUTH SUA PAN AREA (STUDY AREAS 1 AND 2)

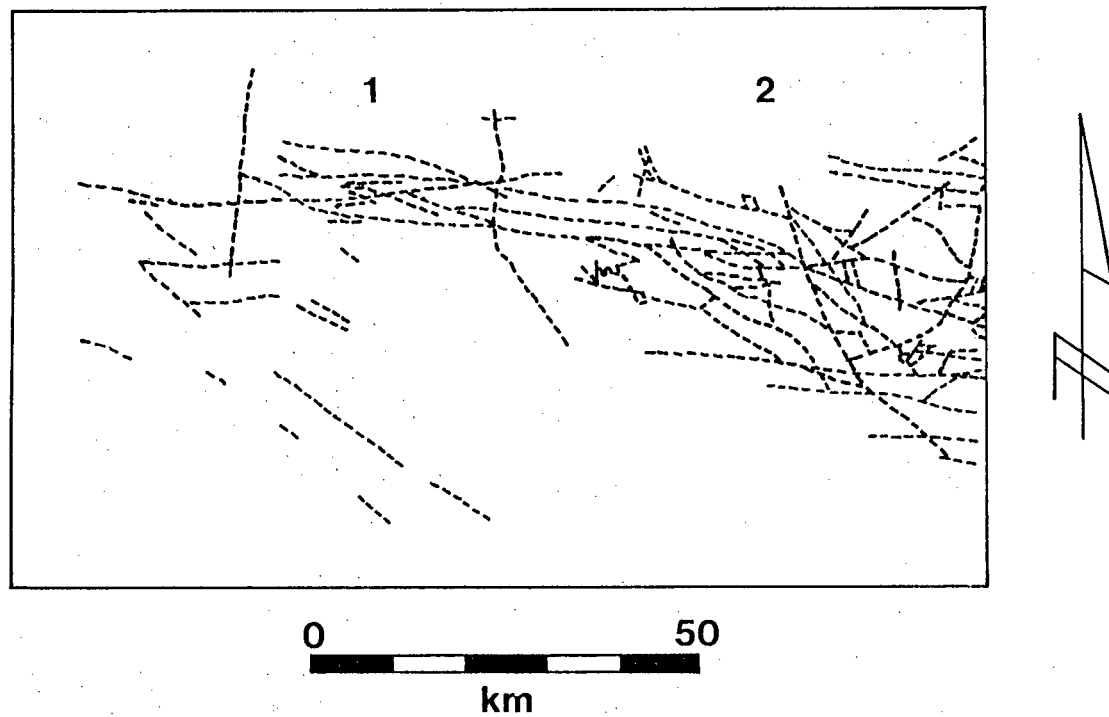
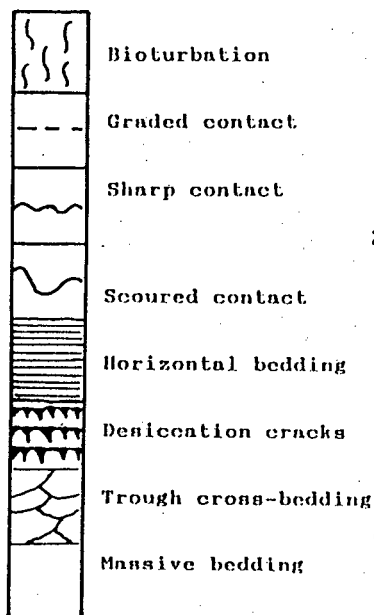
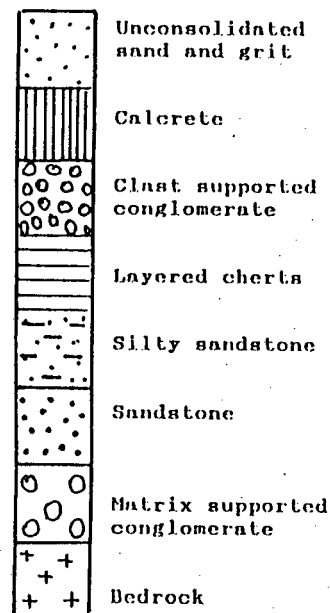


Fig. 5

**GENERALIZED SCHEMATIC PROFILE OF THE SEDIMENTARY SUCCESSION THAT HAS DEVELOPED IN NORTHERN BOTSWANA SINCE THE 90 Ma KIMBERLITE INTRUSIONS (EXCLUDING THE MAKGADIKGADI SEDIMENTS)**

**LEGEND**



METRES

35

30

20

10

0

8

7

6

5

4

3

2

1

Gordonia Formation

Debe Formation

LSF

Mmashoro Sandstone Formation

Kwari Formation

Makoba Subgroup

Orapa Subgroup

Zero Intermediate High  
Energy in depositional environment

Drakensberg basalt

Pre-Kalahari

Clay  
Silt  
Fine sand  
Med sand  
Coarse sand  
Granule  
Pebble  
Cobble  
Boulder

Fig. 6

## MODEL FOR THE STRATIGRAPHIC DISTRIBUTION OF THE MMASHORO SANDSTONE FORMATION

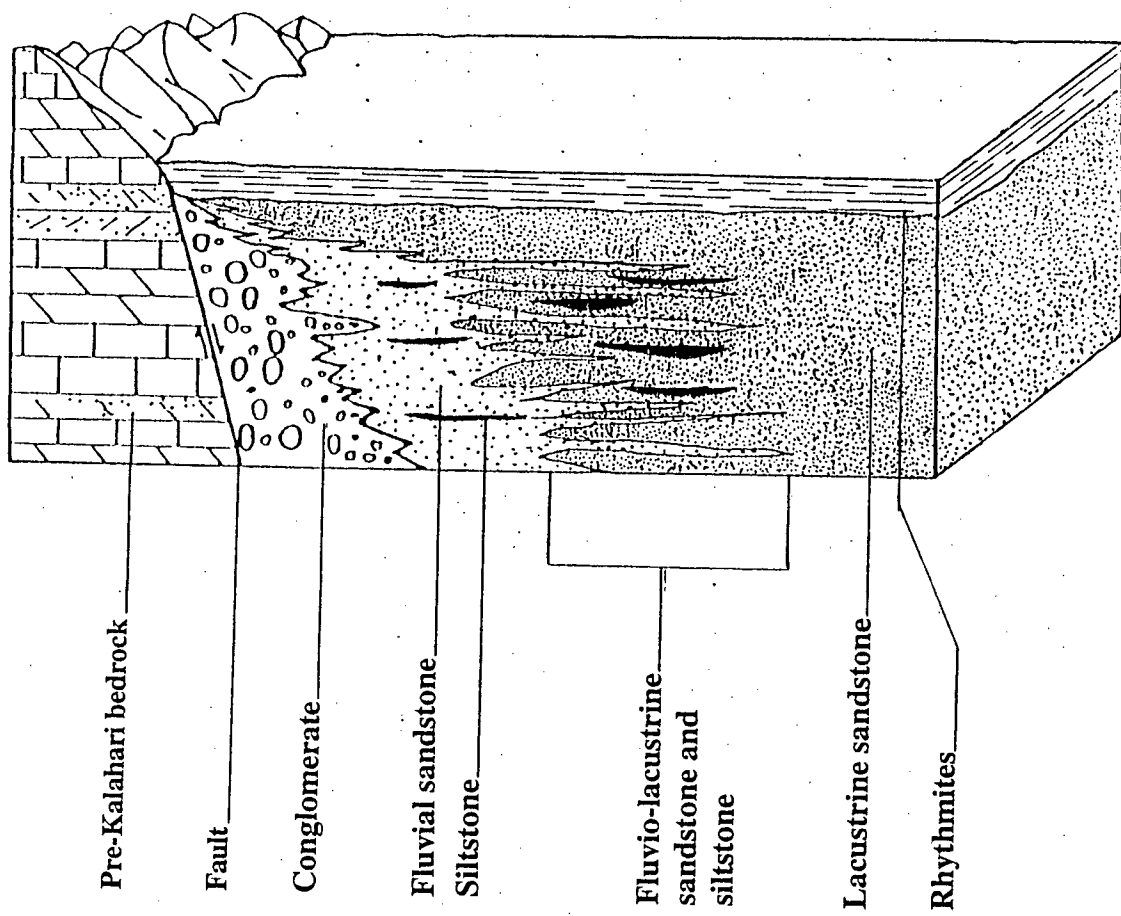


Fig. 7

# PROFILE AT A (ORAPA-LETLHAKANE AREA)

## LÉGEND

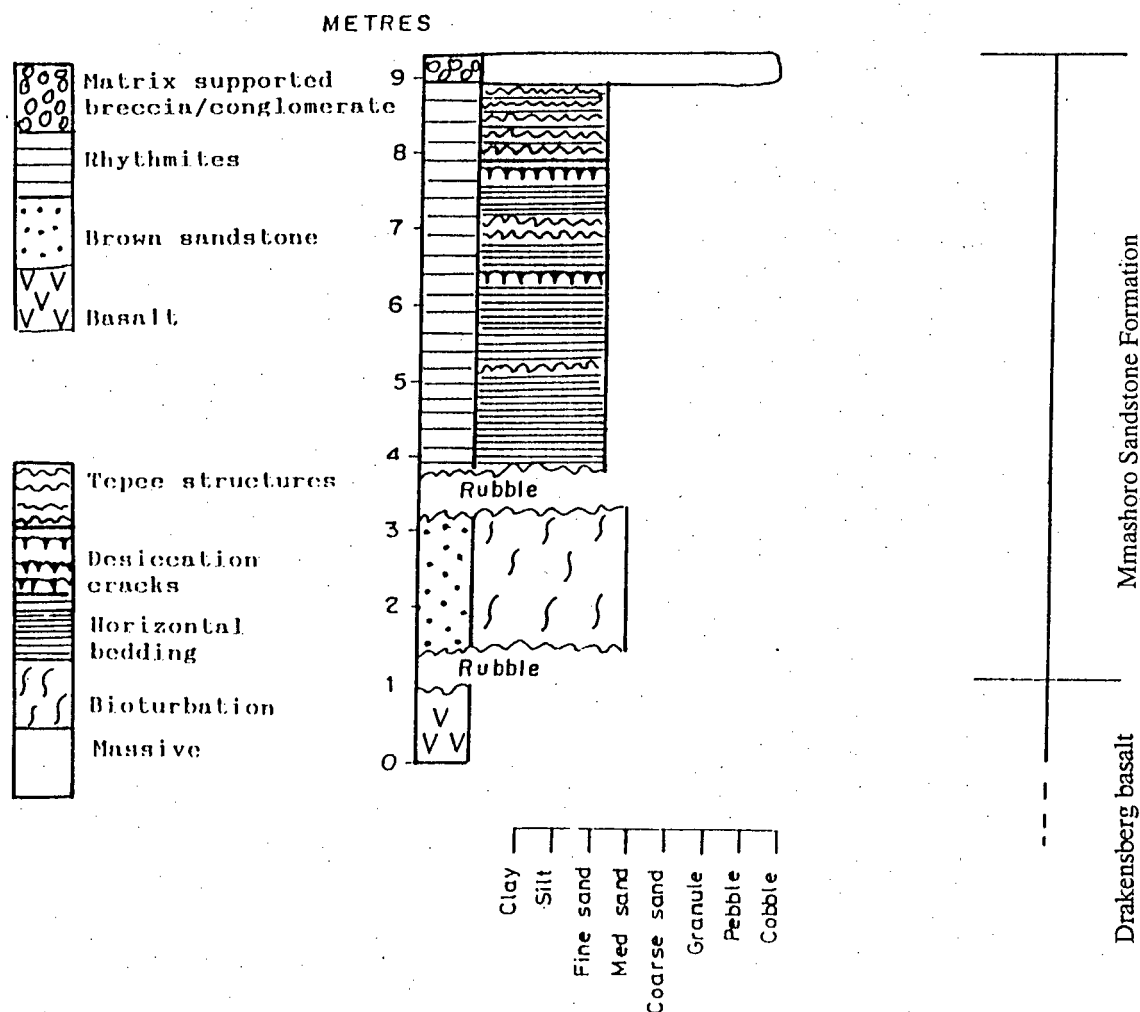
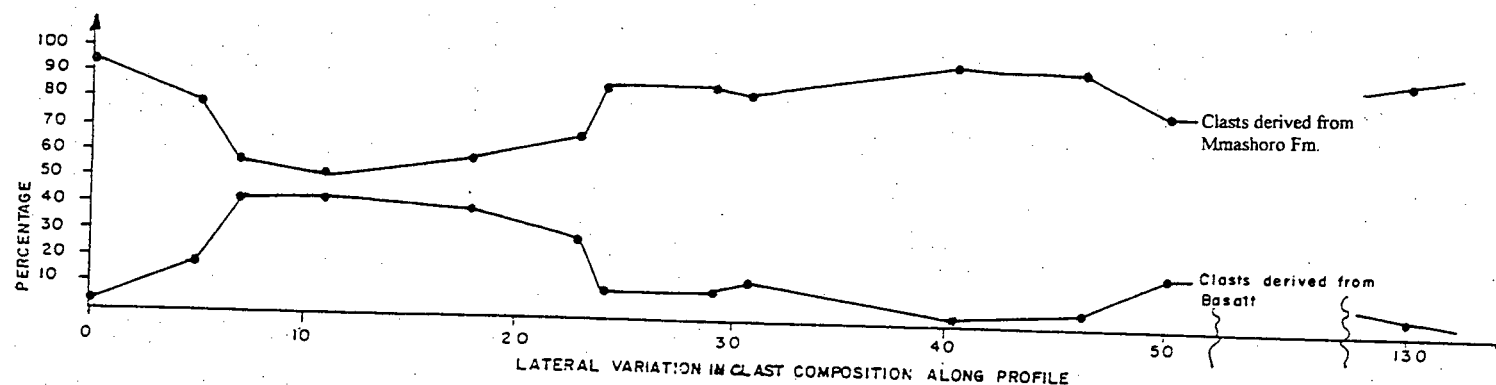


Fig. 8

DIAGRAMS SHOWING THE CLAST COMPOSITION AND PROFILE OF THE LETSHAKANE STONELINE FORMATION TO THE EAST OF D/K 1 AND THE NORTH OF D/K 2 (PROFILE POSITION MARKED ON CONTOURED COMPOSITE MAP)

WEST

EAST



WEST

EAST

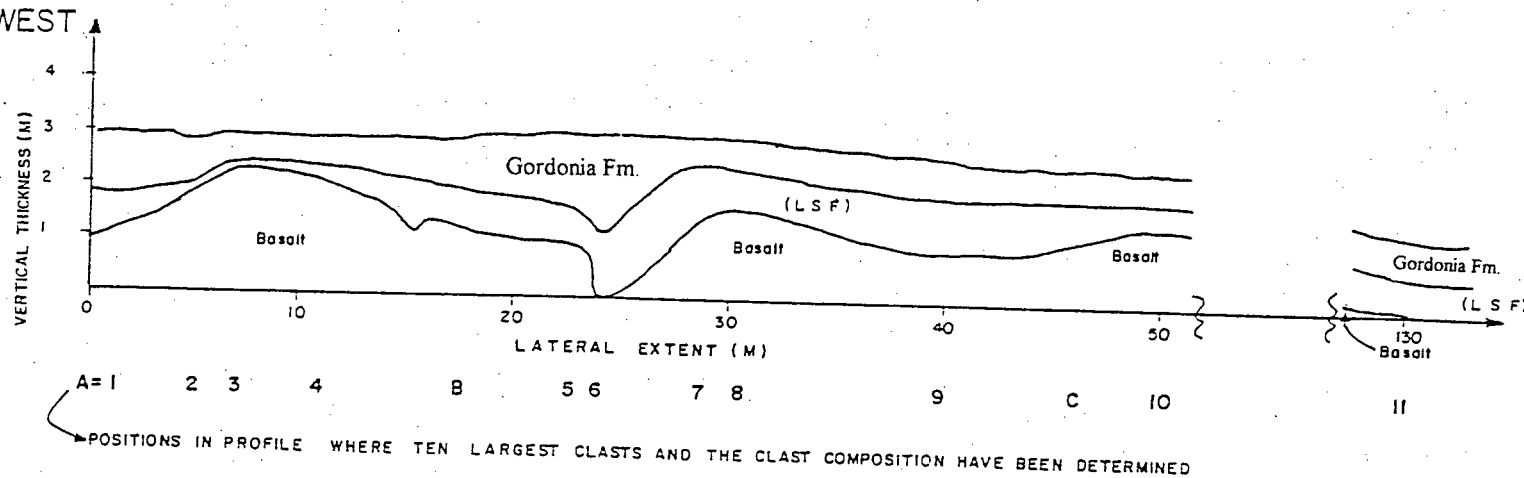


Fig. 9

MEAN PEBBLE SIZE OF THE TEN LARGEST CLASTS AGAINST THE BED-THICKNESS OF THE LETLHAKANE STONELINE FORMATION AROUND KIMBERLITES DK1 AND DK2 (LETLHAKANE MINE)

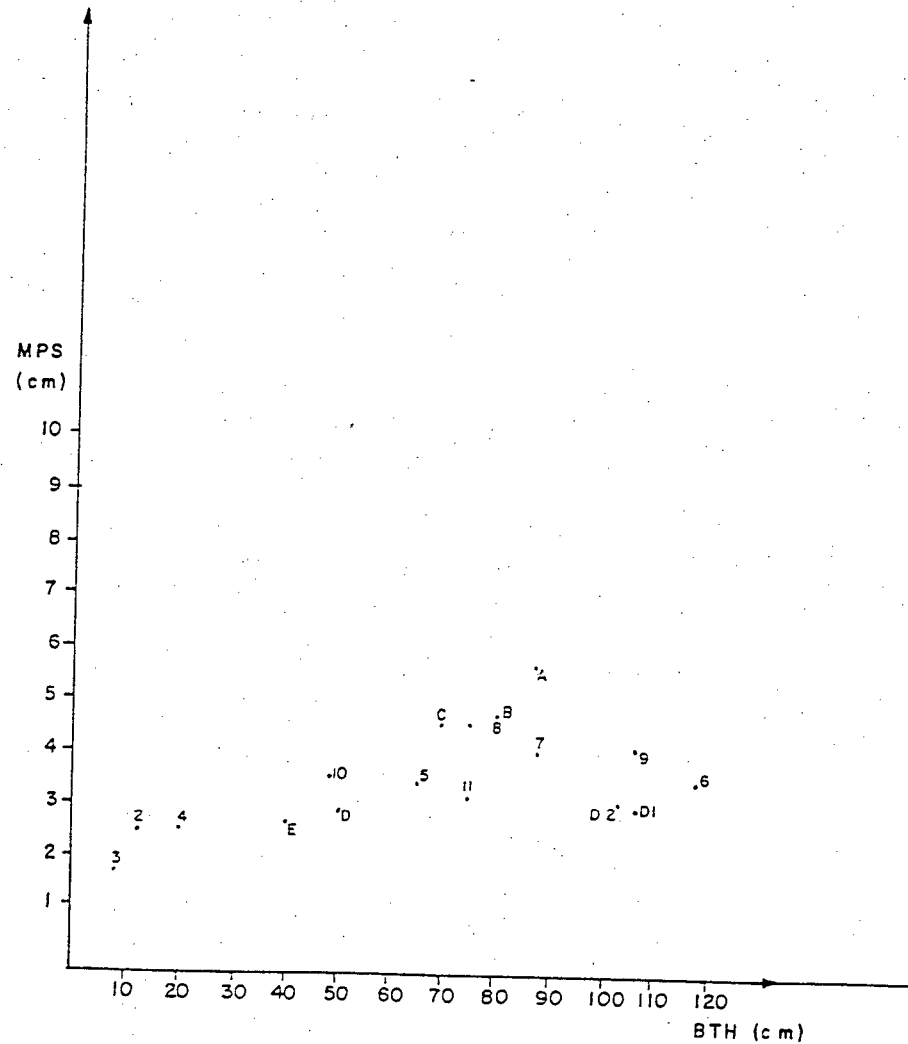


Fig. 10

COMPOSITE MAP OF THE VOLUME OF THE LETLHAKANE STONELINE FORMATION AND THE CONCENTRATION OF HEAVY MINERALS AROUND D/K1 & D/K2

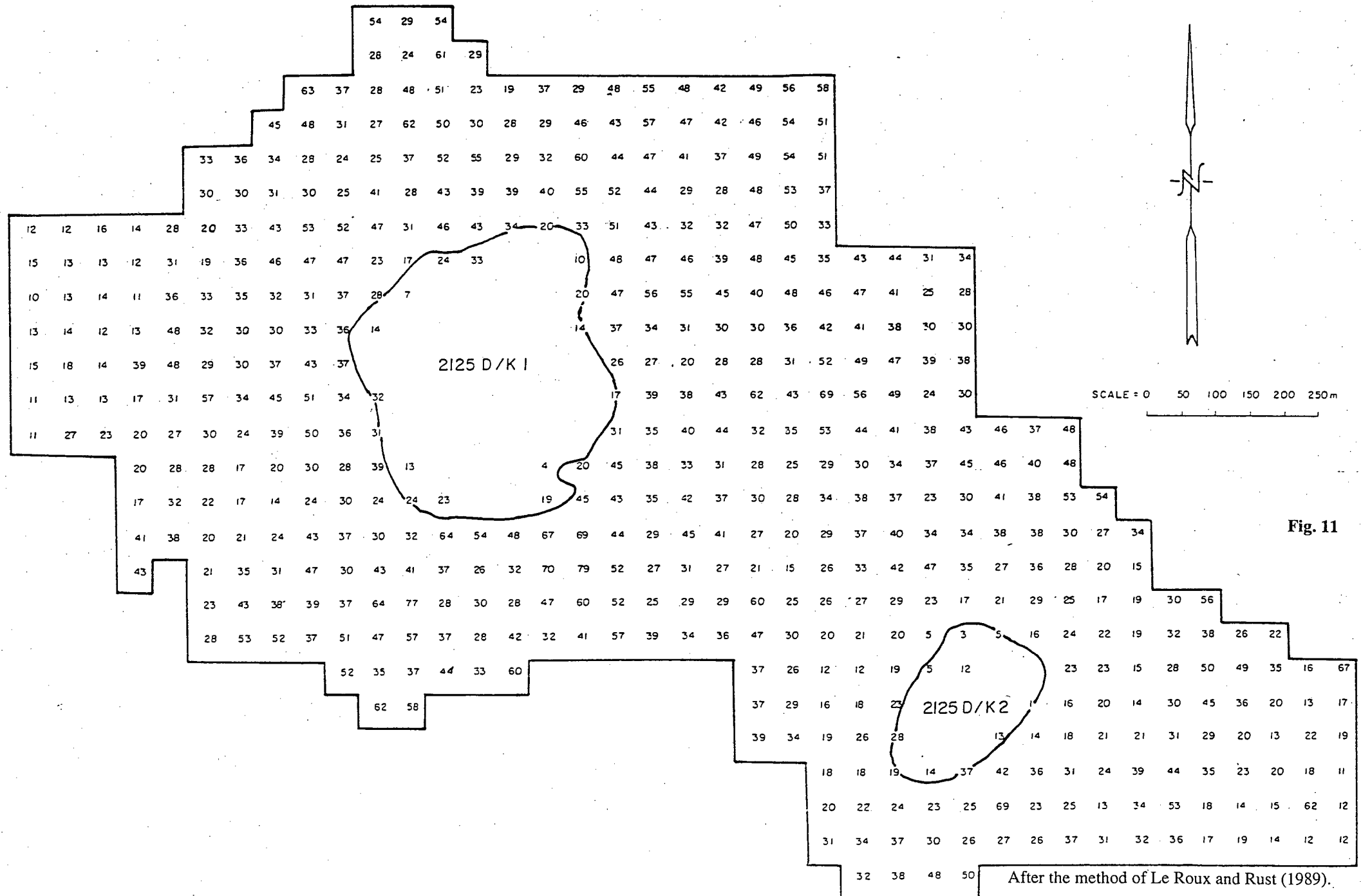
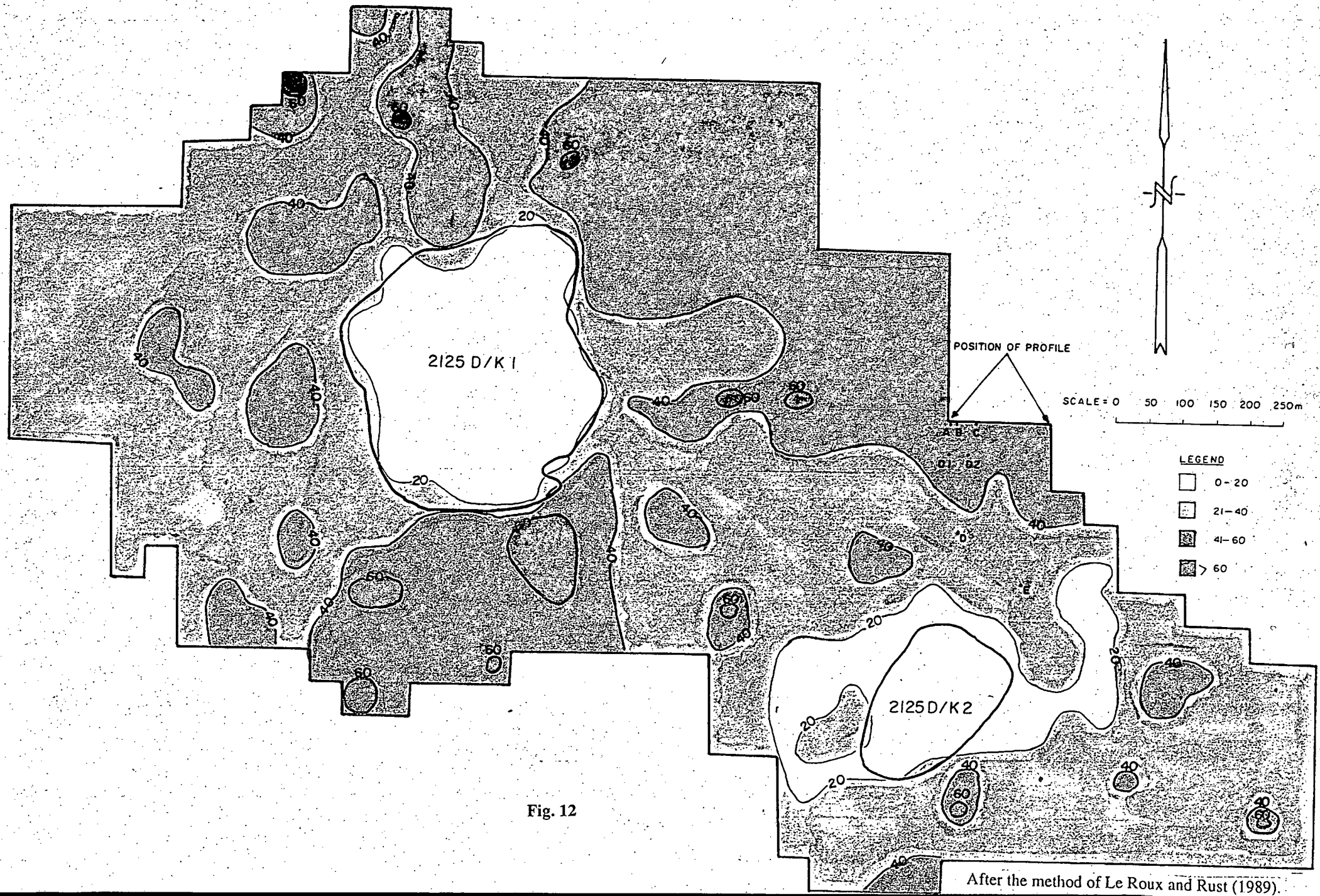


Fig. 11



CONTOURED COMPOSITE MAP AROUND D/K1 & D/K2



TRANSPORT DIRECTIONS FOR GRAVITY FLOWS IN THE LETLHAKANE STONELINE FORMATION

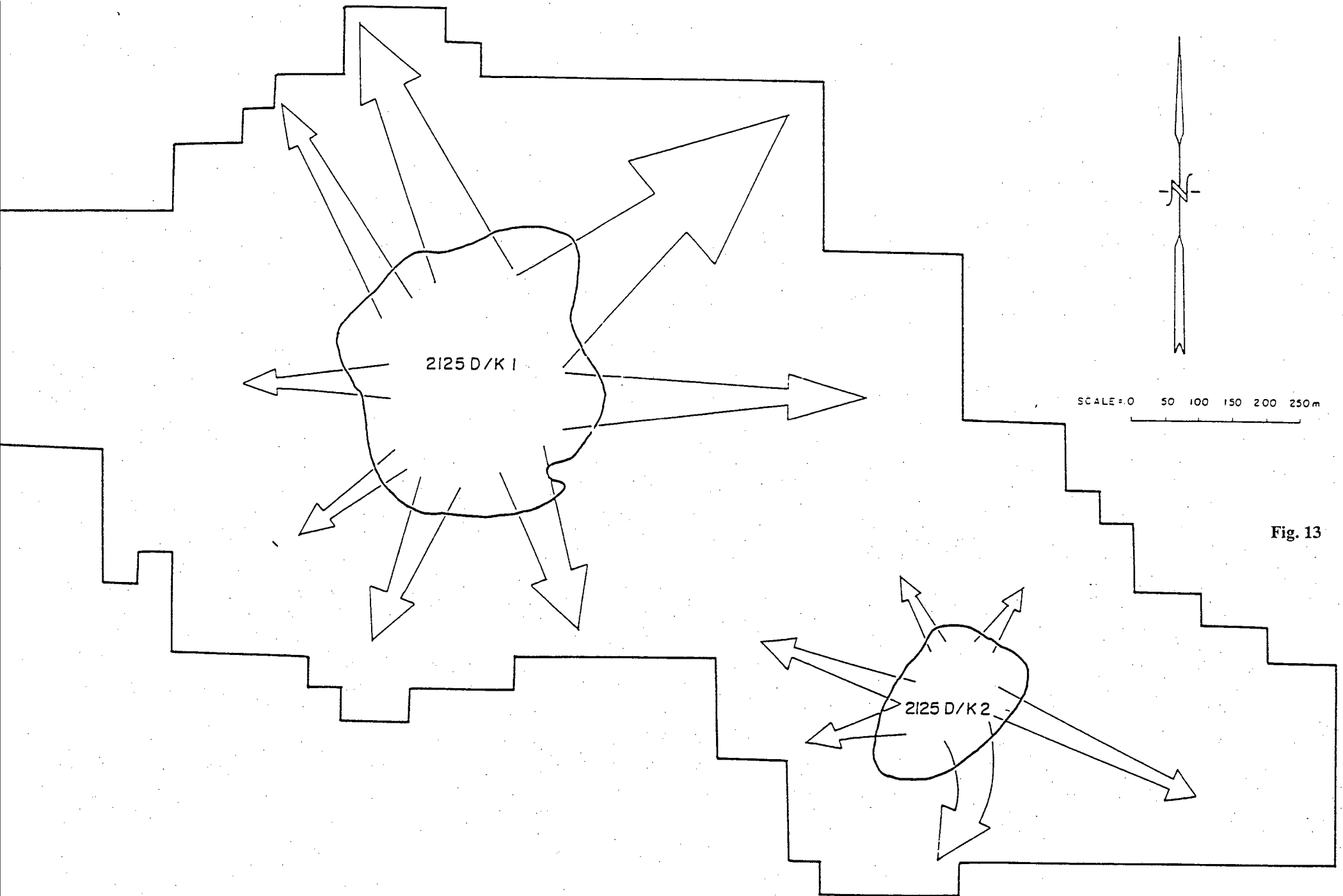
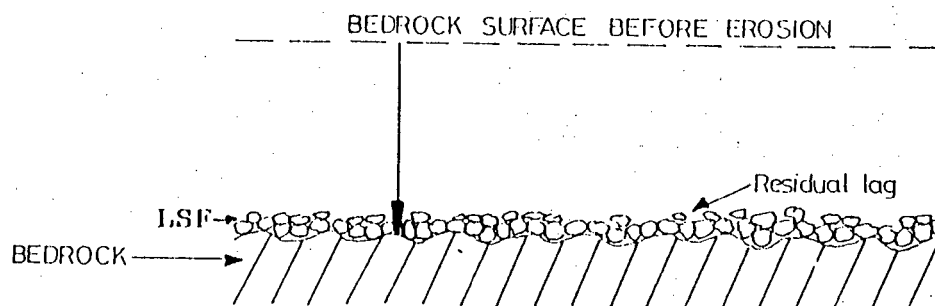


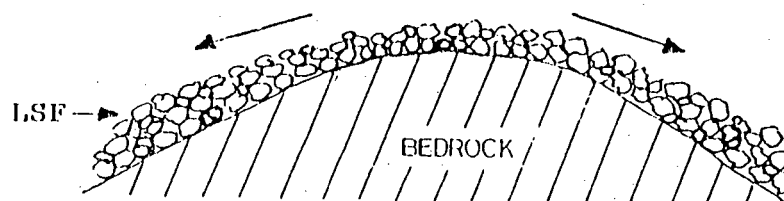
Fig. 13

# THREE MECHANISMS FOR THE FORMATION OF THE LETLIHAKANE STONELINE FORMATION (LSF)

## ① EROSION



## ② GRAVITY FLOW ON PALAEO-HIGHS



## ③ DOWNWARD MIGRATION OF CLASTS AND STONE TOOLS DUE TO BIOTURBATION AFTER THE DEPOSITION OF GORDONIA FM SANDS

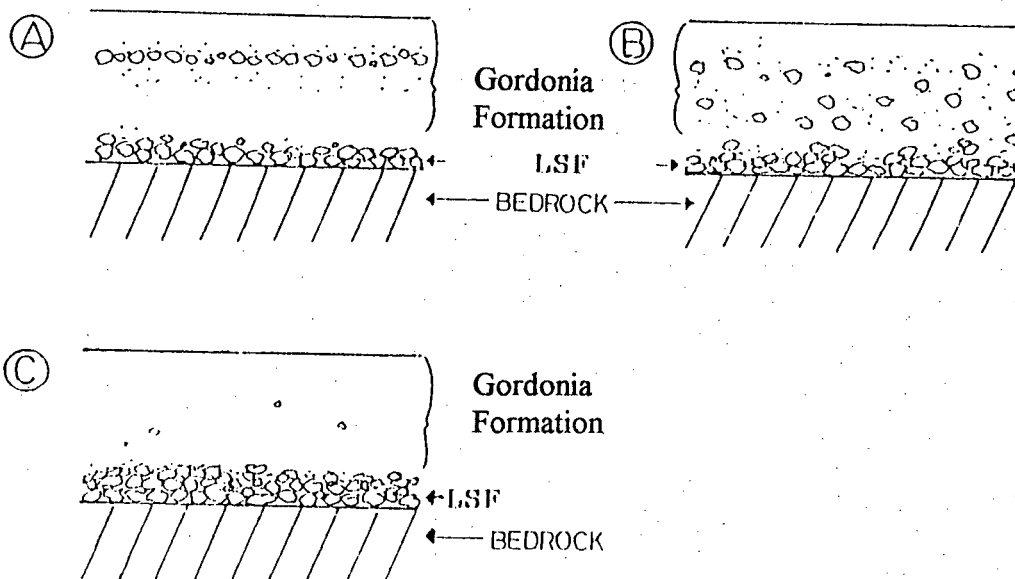


Fig. 14

PLAN VIEW OF THE AREA AT F (SOUTH SVA PAN AREA)

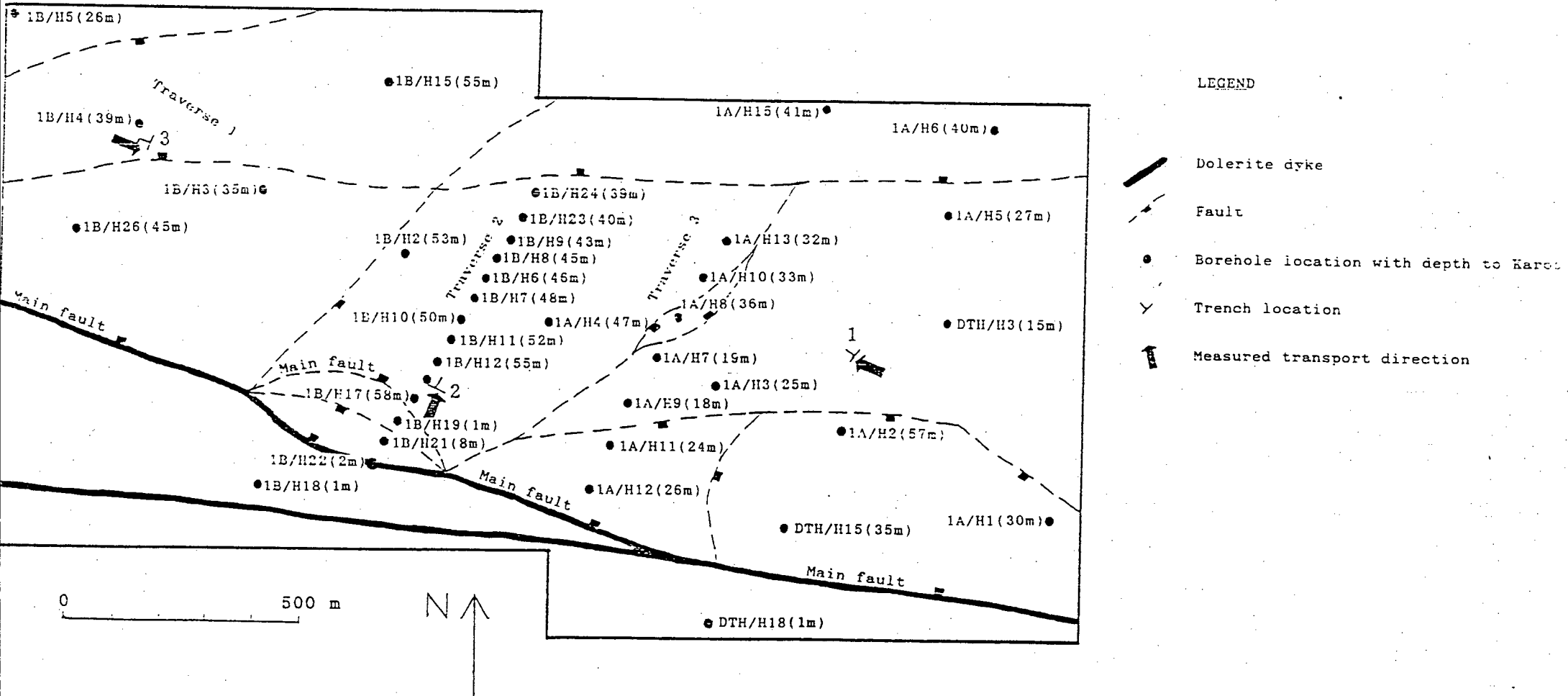


Fig. 15

**LEGEND FOR DRILL TRAVERSES 1, 2 AND 3 AT F (SOUTH SUA PAN AREA).**

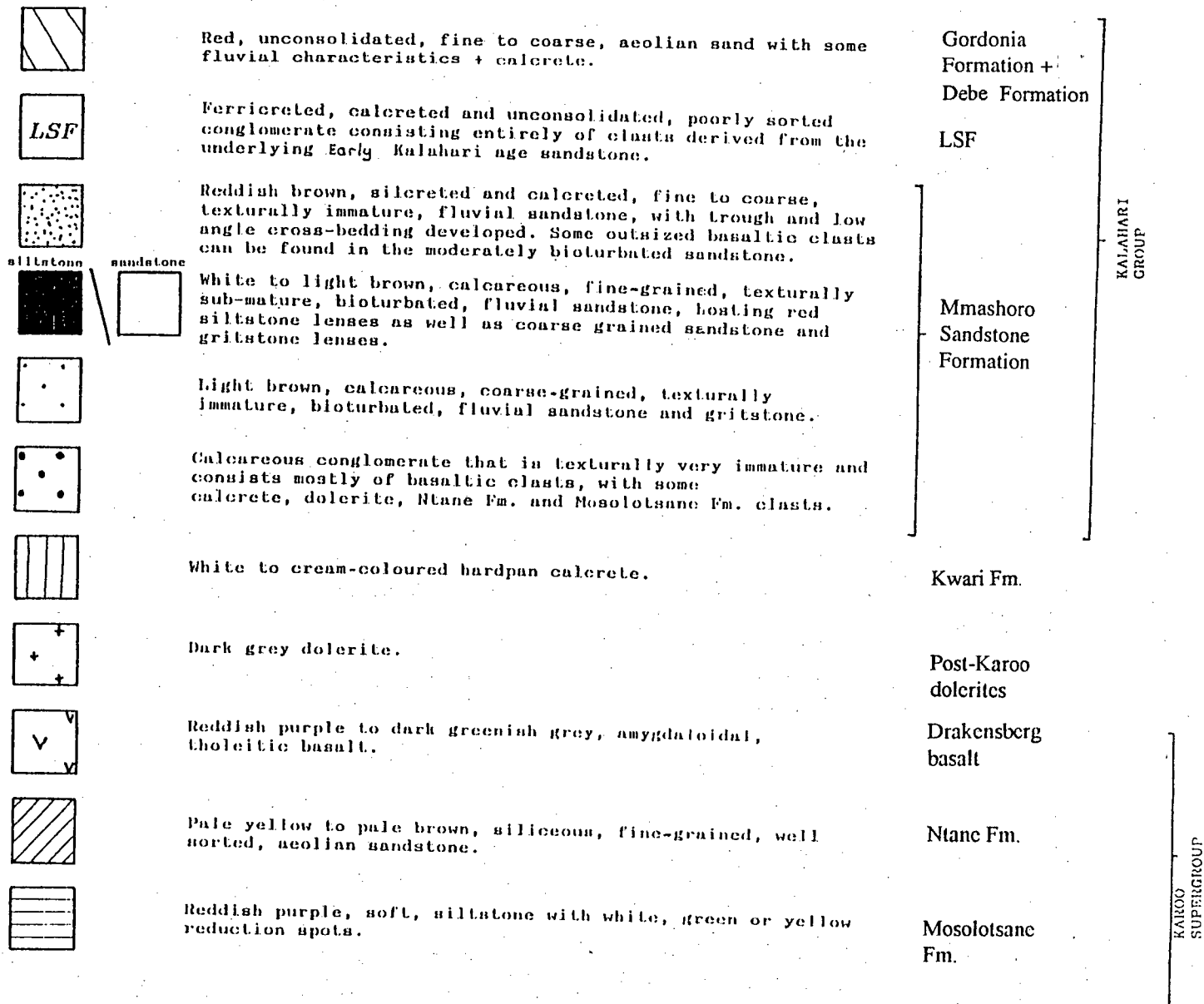


Fig. 16

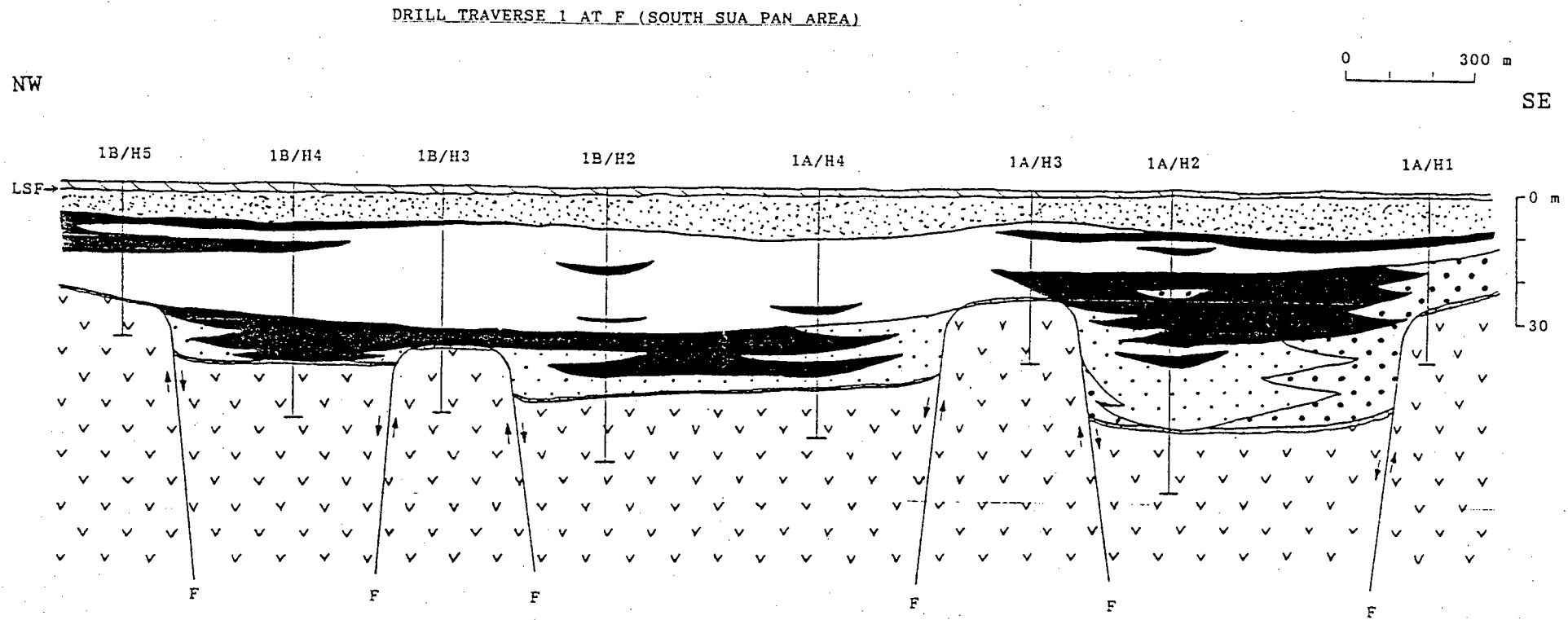


Fig. 17



DRILL TRAVERSE 2 AT F (SOUTH SUA PAN AREA)

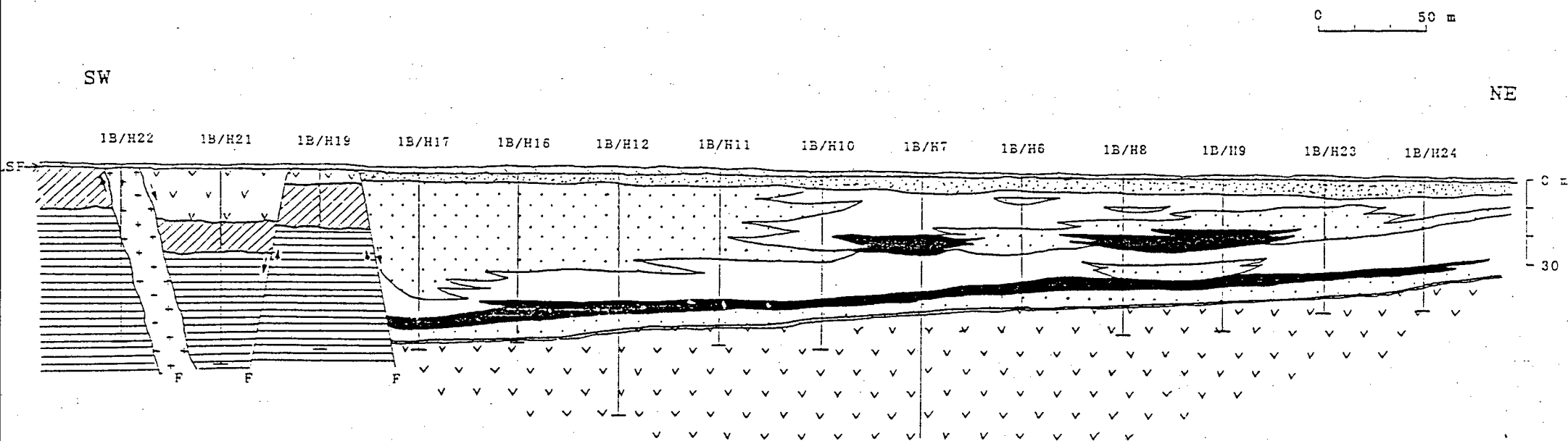


Fig. 18



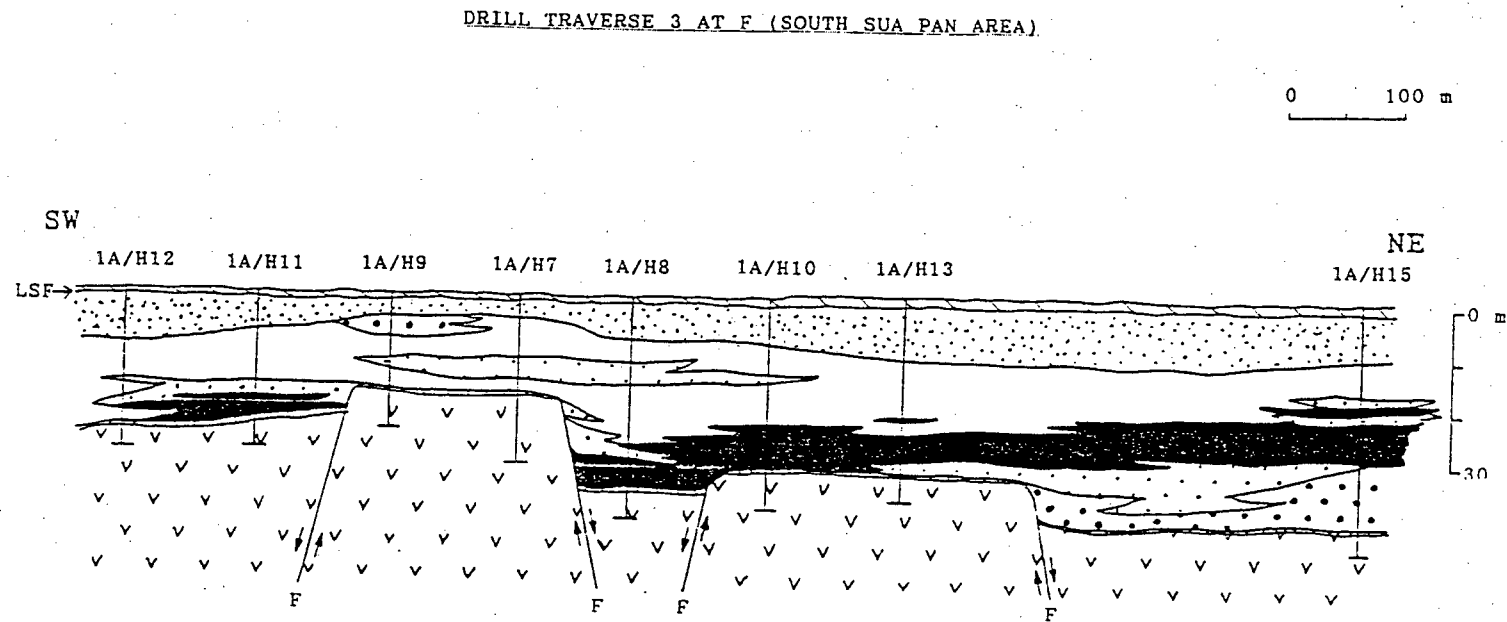
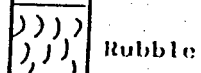
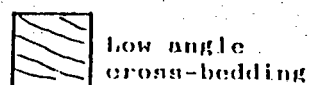
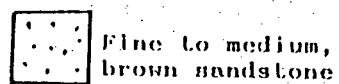


Fig. 19

# PROFILE AT E (SOUTH SUA PAN AREA)

## LEGEND



METRES

2

1

0

Mmashoro Sandstone Formation

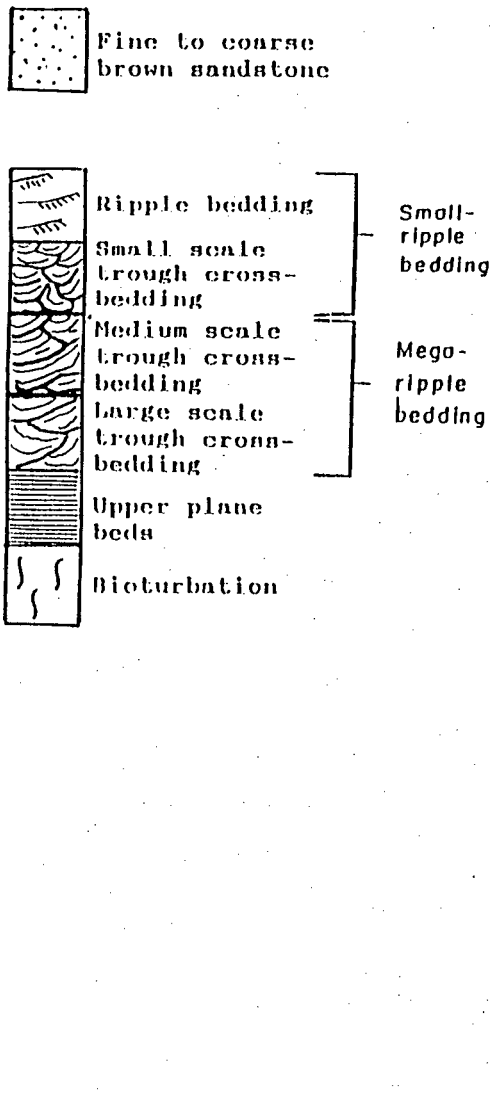
Kalahari  
Group

Clay  
Silt  
Fine sand  
Med sand  
Coarse sand  
Granule

Fig. 20

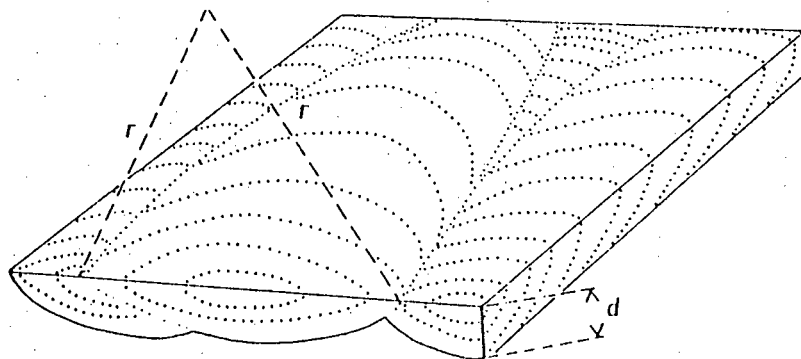
# PROFILE AT A (NATA AREA)

## LEGEND



Trough cross-bed thickness ( C m )	radius ( C m )
1	6
1,5	17
6	38
16	165

Fig. 21



**Fig. 22** Diagram illustrating the definition of trough-shaped small-ripple and megaripple bedding. In small-ripple bedding the radius of the trough ( $r$ ) is less than 20 cm, and thickness ( $d$ ) is less than 4 cm. For megaripple bedding the radius of the trough ( $r$ ) is more than 20 cm, and the thickness ( $d$ ) is more than 4 cm.

# PROFILE AT A1 (MMASHORO AREA)

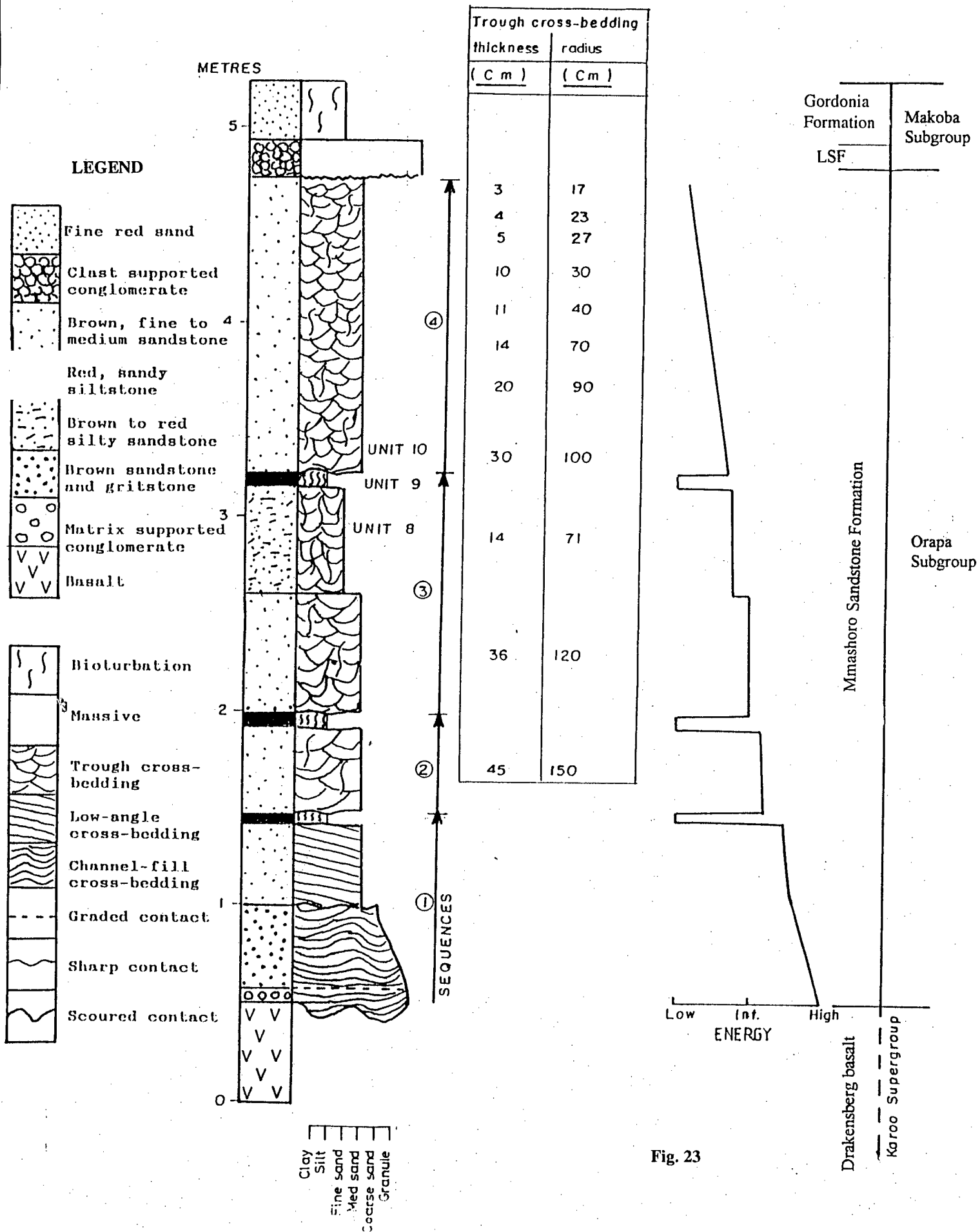
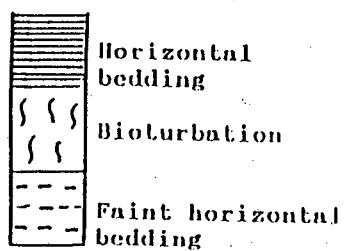
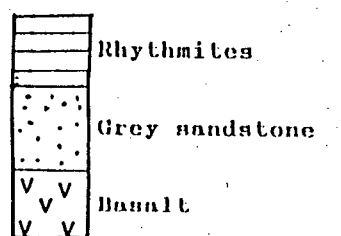


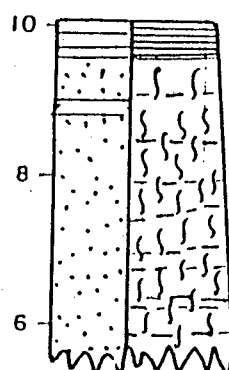
Fig. 23

# COMBINED SCHEMATIC PROFILE AT B1 AND B2 (MMASHORO AREA)

## LEGEND



METRES



RUBBLE

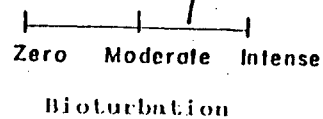
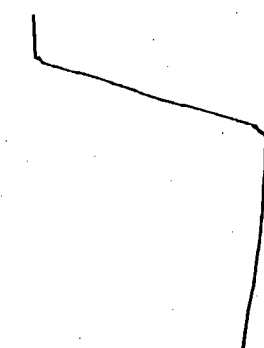
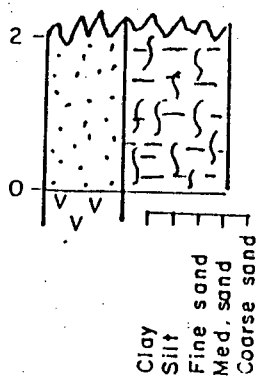


Fig. 24

# PROFILE AT C (MMASHORO AREA)

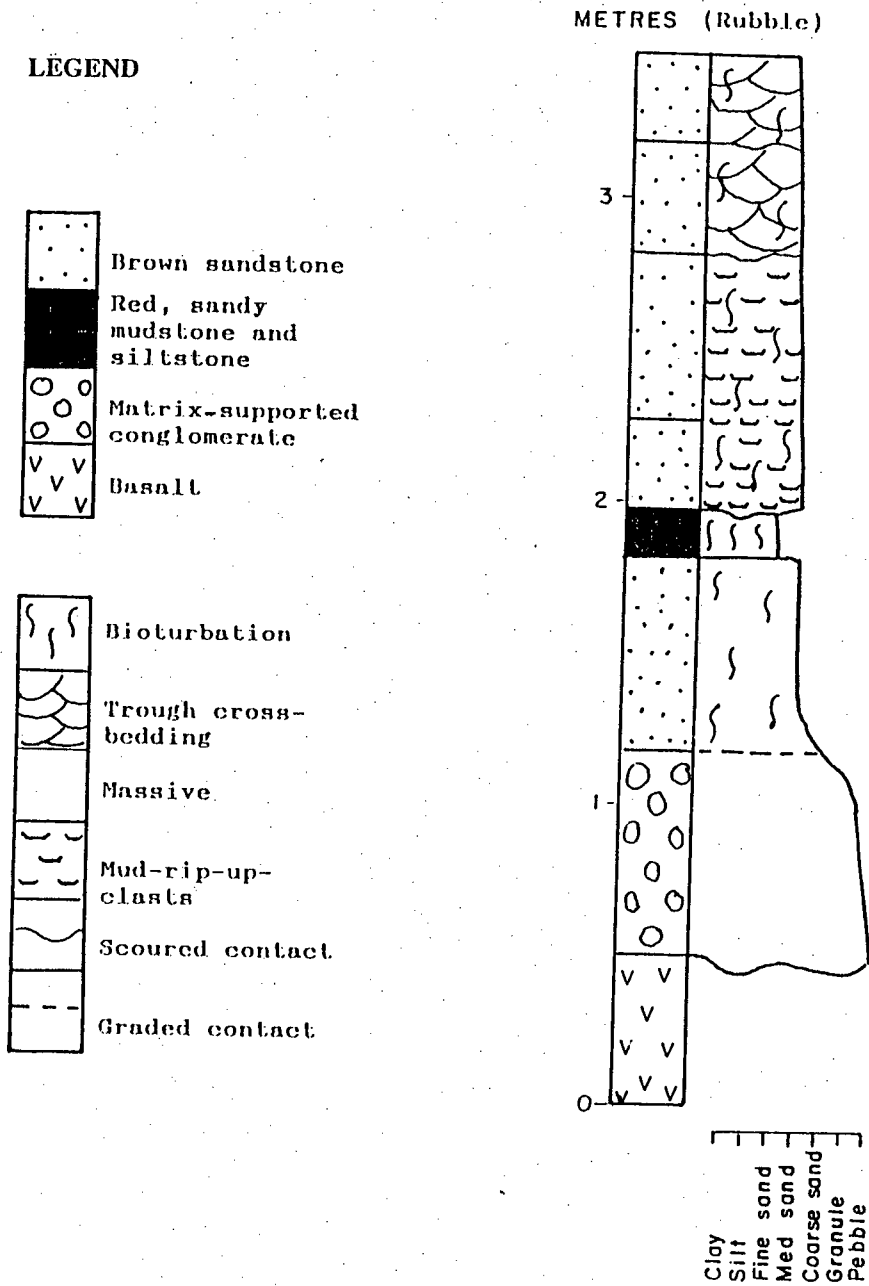
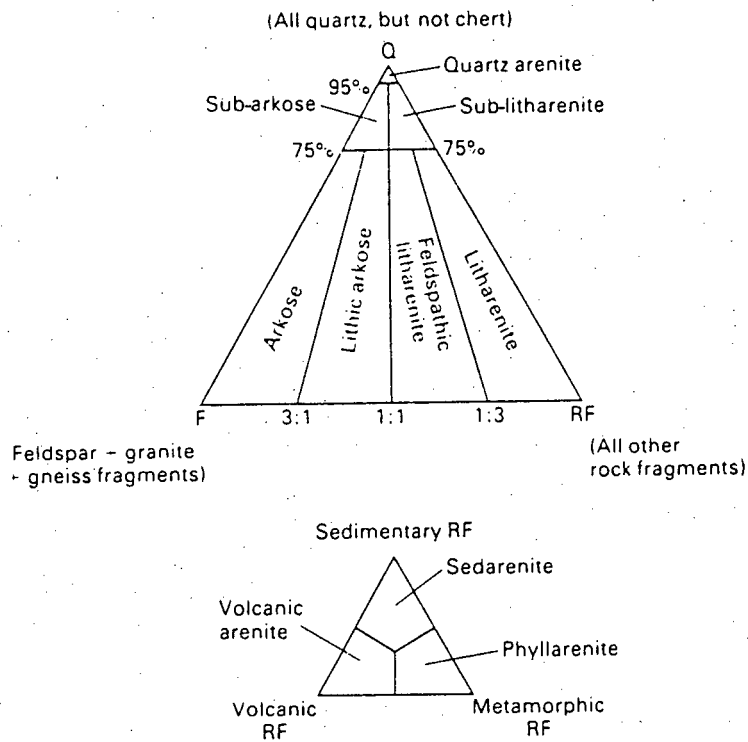


Fig. 25





**Fig. 26** Classification of sandstones. The upper triangle shows a sandstone classification for sediments with less than 15% fine-grained matrix. Classification involves the removal of matrix, cement, micas etc, and recalculation of components to 100%. The lower triangle shows how litharenites may be further classified. (From Folk, 1974)

Original components not organically bound together during deposition				Components organically bound during deposition
contains carbonate mud			no carbonate mud	
mud-supported		grain-supported		
< 10% allochems	> 10% allochems			
MUDSTONE	WACKESTONE	PACKSTONE	GRAINSTONE	

**Fig. 27** Classification of limestones according to Dunham (1962) Rock names are in capital letters

*Grain-size classification of sediments*

Size in mm of class boundary	Class term	Grain size terms for rock	
256 —	boulders	rudite rudaceous rock conglomerate breccia	
64 —	cobbles		
4 —	pebbles		
2 —	granules		
1 —	very coarse sand	arenite arenaceous rock sandstone	
0.5( $\frac{1}{2}$ ) —	coarse sand		
0.25( $\frac{1}{4}$ ) —	medium sand		
0.125( $\frac{1}{8}$ ) —	fine sand		
0.0625( $\frac{1}{16}$ ) —	very fine sand		
0.0312( $\frac{1}{32}$ ) —	coarse silt	siltstone	argillite argillaceous rock mudstone mudrock shale
0.0156( $\frac{1}{64}$ ) —	medium silt		
0.0078( $\frac{1}{128}$ ) —	fine silt		
0.0039( $\frac{1}{256}$ ) —	very fine silt		
	clay	claystone	

**Fig. 28**

(13) PLATES

Plate 1



Ntane Formation

Mosolotsane Formation

Brown, aeolian Ntane sandstone overlying red, fluvial Mosolotsane siltstone (South Sua Pan Area).

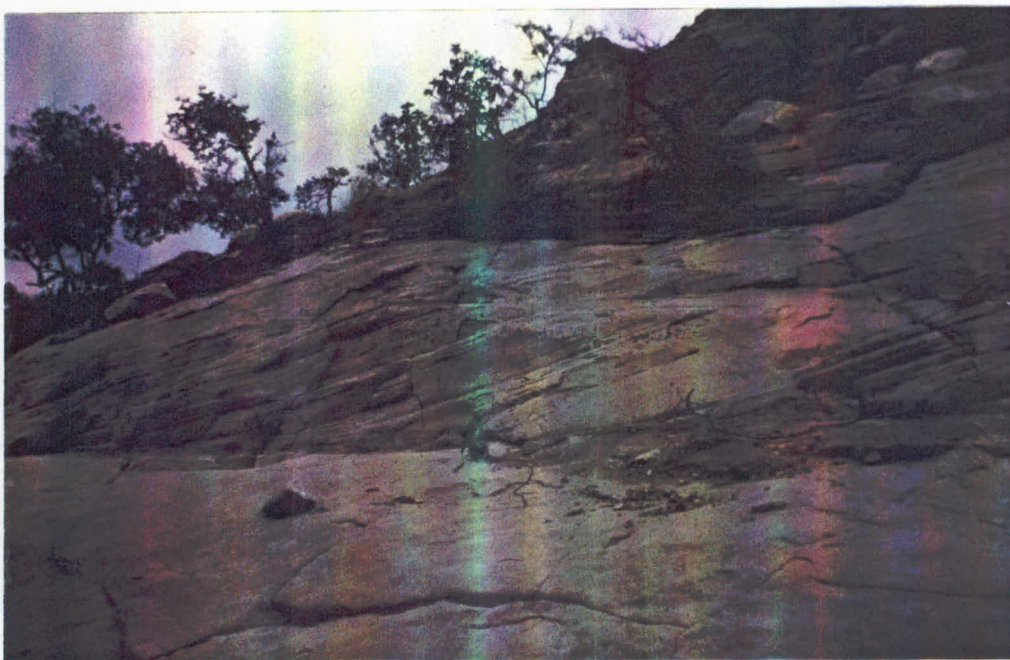


Plate 2

1m

Large scale, aeolian cross-bedding in the Ntane Sandstone Formation (South Sua Pan Area).

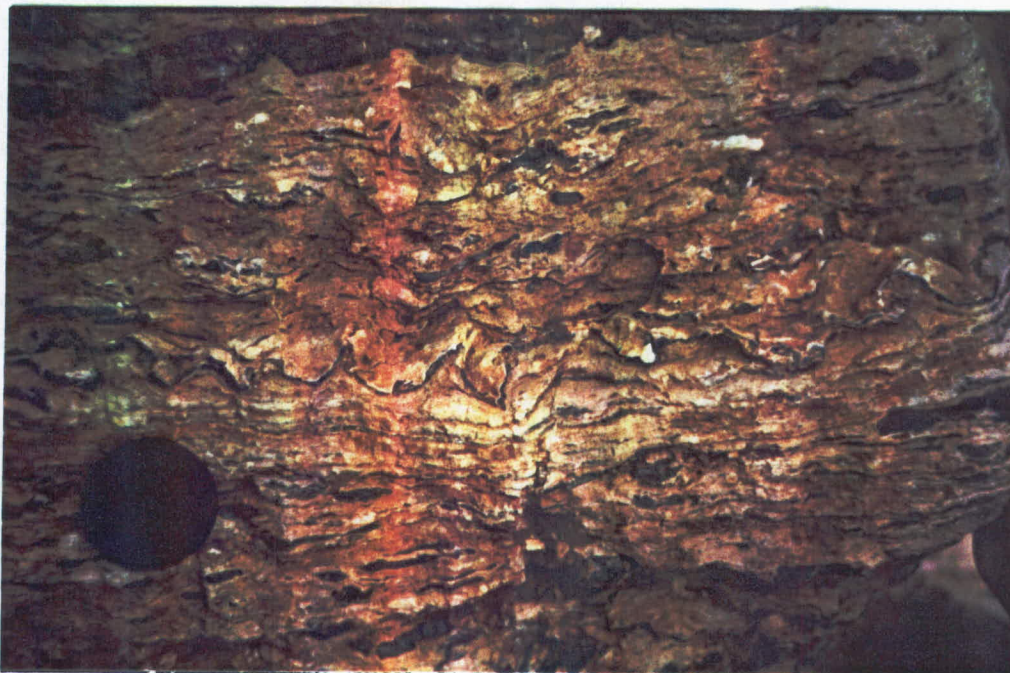


Plate 3



Lacustrine rhythmites with some tepee-structures at A (Orapa-Letlhakane Area). In fresh exposures the sandstone is green in colour.

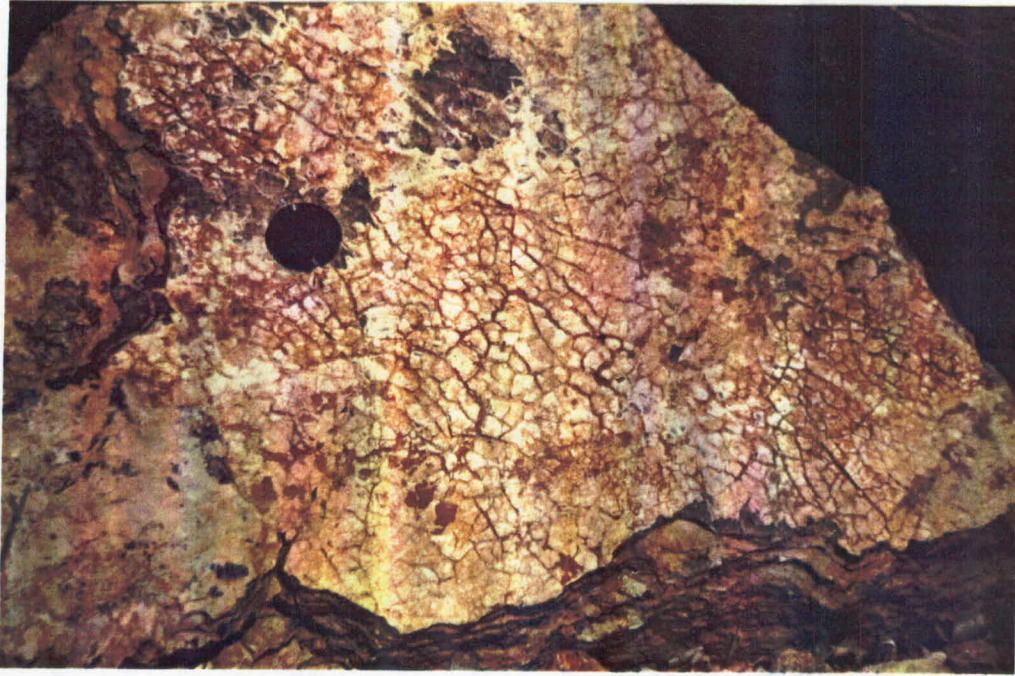
Plate 4



Tepee-structures in the layered cherts at A (Orapa-Letlhakane Area). The lens cover has a diameter of 55 mm.



Plate 5



Fresh exposure of desiccation cracks and iron-oxides on the upper surface of a chert layer at A (Orapa-Letlhakane Area). The lens cover has a diameter of 55 mm.

Plate 6



Desiccation cracks with saline mineral growth in sandstone of the Mmashoro Sandstone Formation (Orapa-Letlhakane Area).



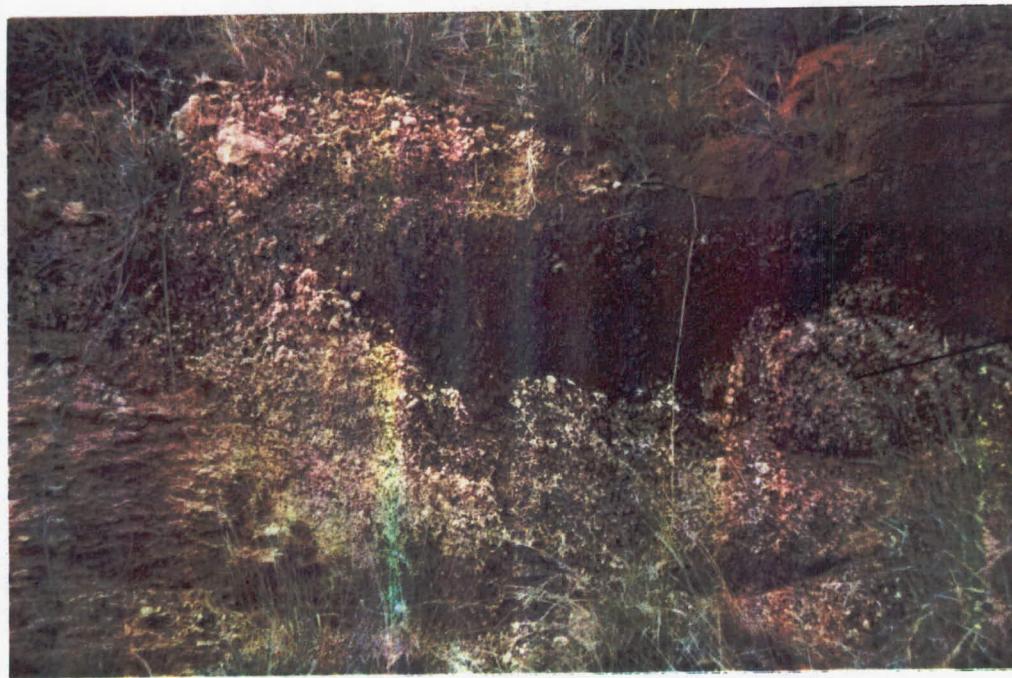


Plate 7

Gordonia Fm.

Ferricreted

Calcreted

LSF

1 m

Late Kalahari age deposits at the Letlhakane Mine.

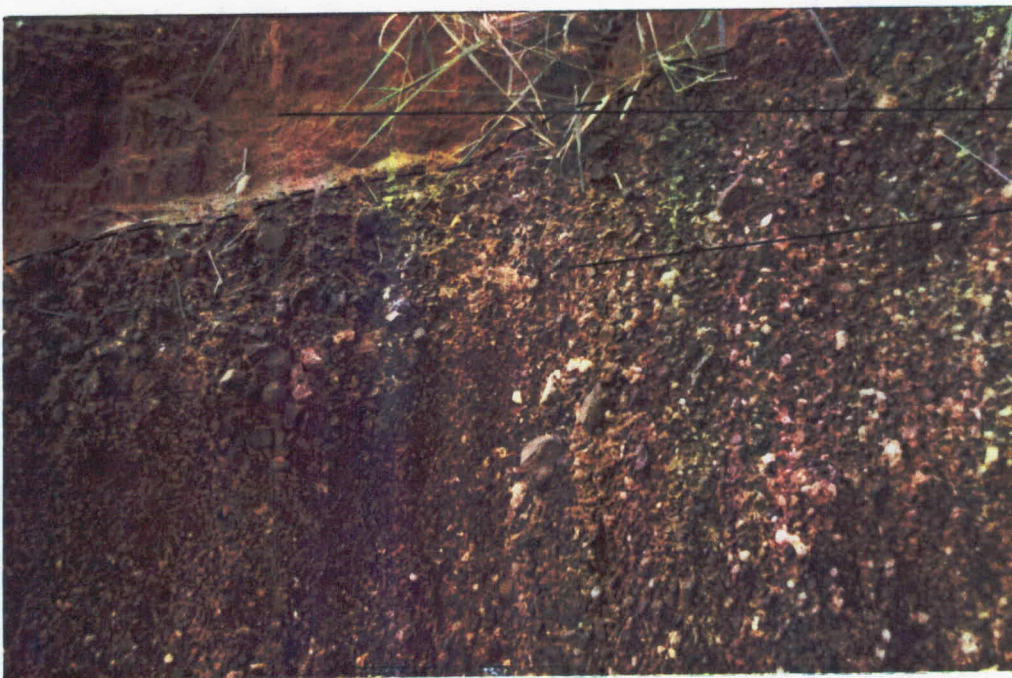


Plate 8

Gordonia Fm.

LSF

50 cm

Late Kalahari age deposits at the Letlhakane Mine.



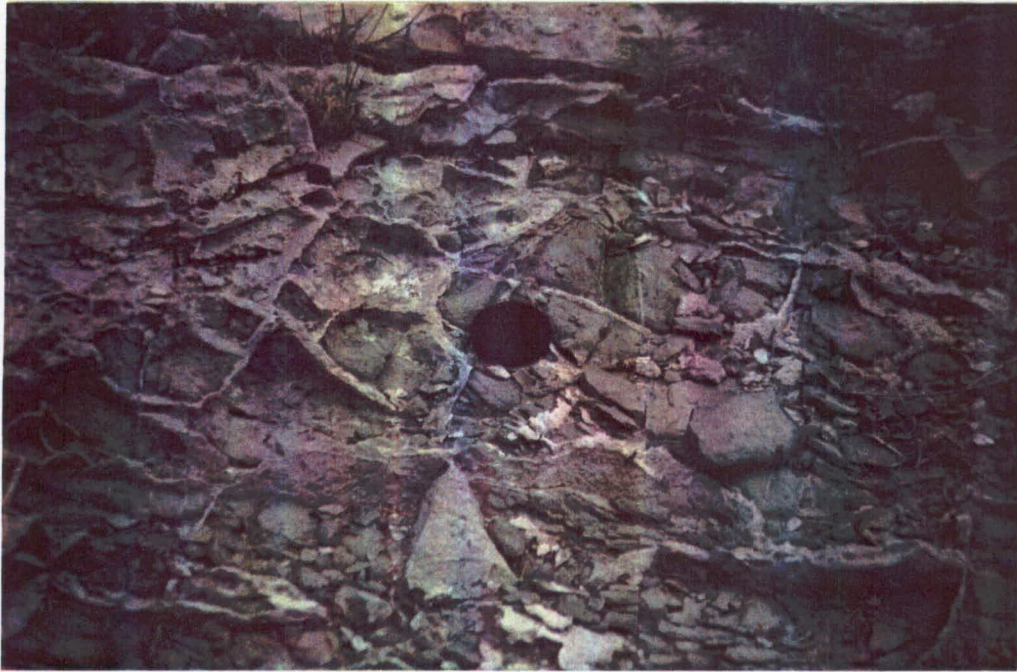


Plate 9

Green glauconite-rich, lacustrine siltstones north of Mosu village (Sample PdP/JPLR/Mos/LS, Appendix 1). Calcrete infilled cracks and bedding planes in the lacustrine deposit.

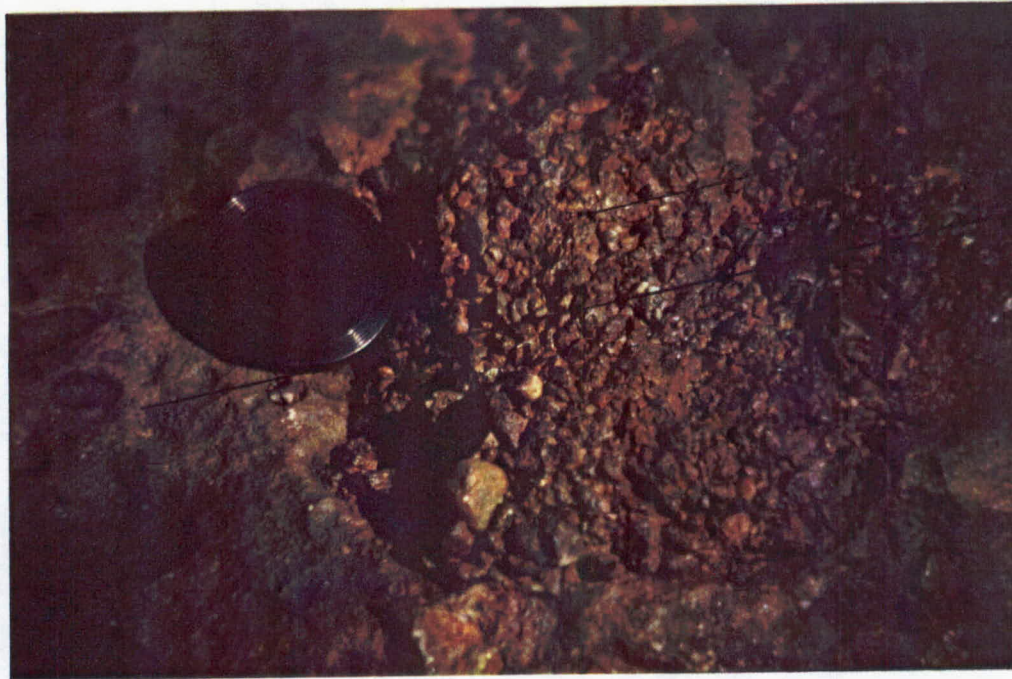


Plate 10

Back-filled Tigillites trace fossil in fluvial sandstone of the Mmashoro Formation (South Sua Pan Area). The lens cover has a diameter of 55 mm.



Plate 11



LSF

Ntane sandstone

Ferricreted LSF, overlying the Ntane Sandstone Formation at D (South Sua Pan Area).

Plate 12



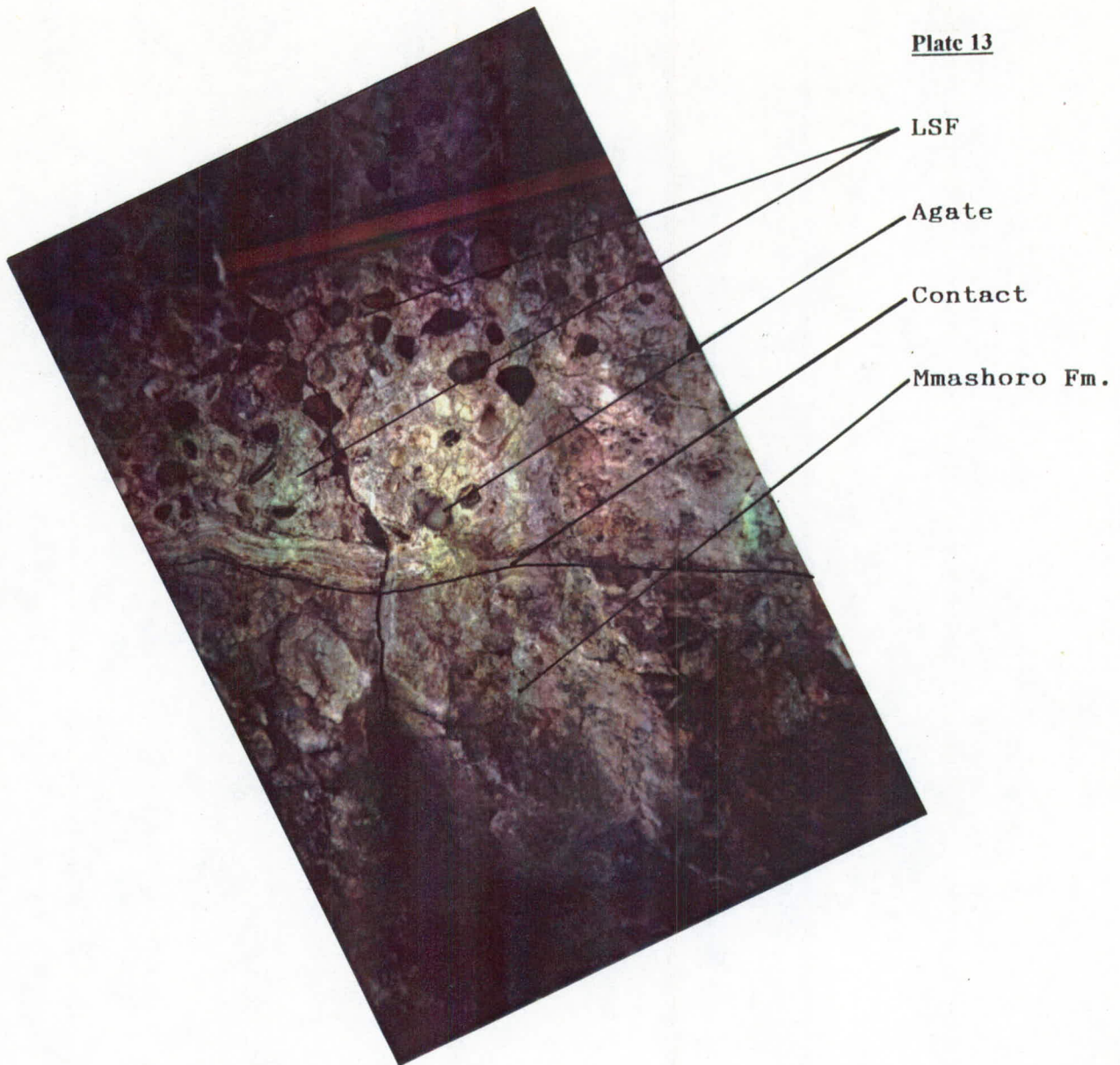
Gordonia Fm.

LSF

Mmashoro Fm.

Unconsolidated sand of the Gordonia Formation overlying an unconsolidated part of the LSF which in turn, overlies calcreted sandstone of the Mmashoro Formation at borrow-pit 14 (South Sua Pan Area).

Plate 13



Clean (no iron-oxide coatings), calcareated conglomerate of the LSF overlying fluvial sandstone of the Mmashoro Sandstone Formation at borrow-pit 14 (South Sua Pan Area).





**Plate 14**

Gordonia Fm.

LSF

Late Kalahari age deposits at the Letlhakane Mine. Dissolution of the calcrete that covers the LSF resulted in the "karst" surface.



**Plate 15**

Late Kalahari age deposits at the Letlhakane Mine. Dissolution of the calcrete that covers the LSF resulted in the "karst" surface.





Plate 16

Displacing and replacing effects of the calcretization process on an outcrop of red Mosolotsane siltstone (South Sua Pan Area).



Plate 17

The displacing (contortions and folding) and replacing effects of the calcretization process can be seen in this outcrop of the Mosolotsane Formation.





Plate 18

Sandstone

Siltstone

Red, bioturbated siltstone lens in the bioturbated fluvial sandstones at A2 (Mmashoro Area).



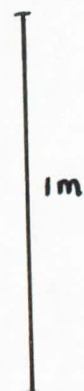
Plate 19

Vertical gypsum growth between sandstone beds of the Mmashoro Formation at A1 (Mmashoro Area). The lens cover has a 55 mm diameter.





Plate 20



The bioturbated top surface (brown) of a Mmashoro sandstone bed at B2 (Mmashoro Area), with a vertical section (white) through the sandstone. Brown *Thalassinoides* burrows are also exposed in the vertical section with some of the burrow openings visible on the brown bedding plane (see also plates 22 and 23).



Plate 21

Strongly bioturbated, Early Kalahari age Mmashoro sandstone at B2 (Mmashoro Area).





Plate 22

The top surface of a Mmashoro sandstone bed at B2, showing the openings of trace fossils on the bedding plane. The lens cover has a 55 mm diameter.



Plate 23

A close-up of the openings of trace fossils on the top surface of a sandstone bed at B2 (Mmashoro Area). The lens cover has a 55 mm diameter.

Plate 24



The branching 3D network of trace fossils in the intensely bioturbated lacustrine sediments of the Mmashoro Formation at B1 (Mmashoro Area). In this rock, the surrounding sediments have weathered away, while the silcreted trace fossils remained. The lens cover has a 55 mm diameter.



(B) PHOTOMICROGRAPHS OF SOME THIN SECTIONS

**Plate 25**

Sample: PdP/BK/L1

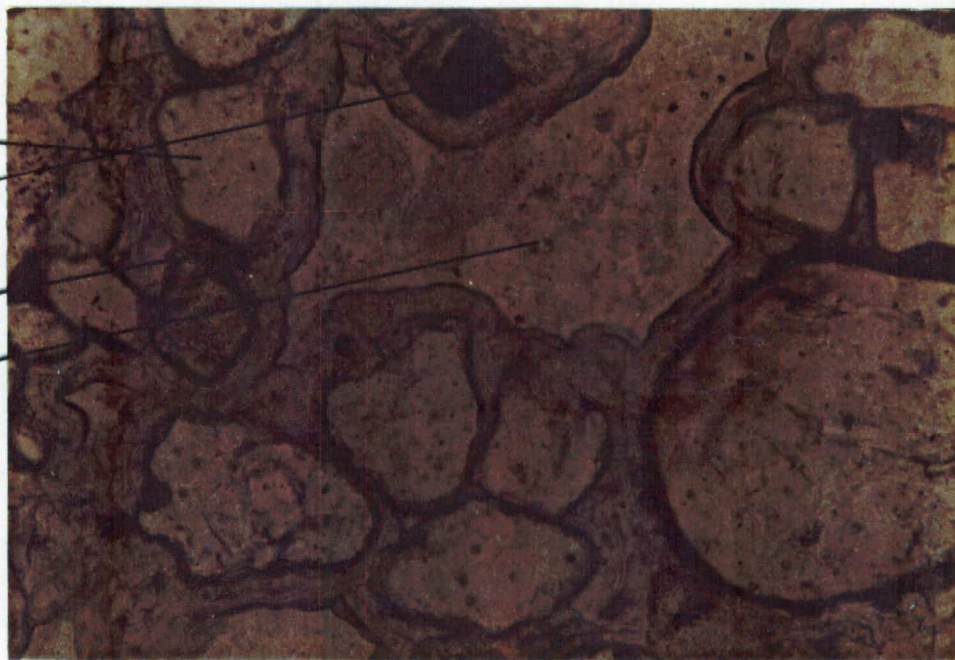
Plane-polarized light (PPL)

Quartz

Opaque heavy mineral

Calcium carbonate (Micrite)

Silica (Chalcedony)



0.5 mm

## Plate 26

Sample: PdP/BK/L1

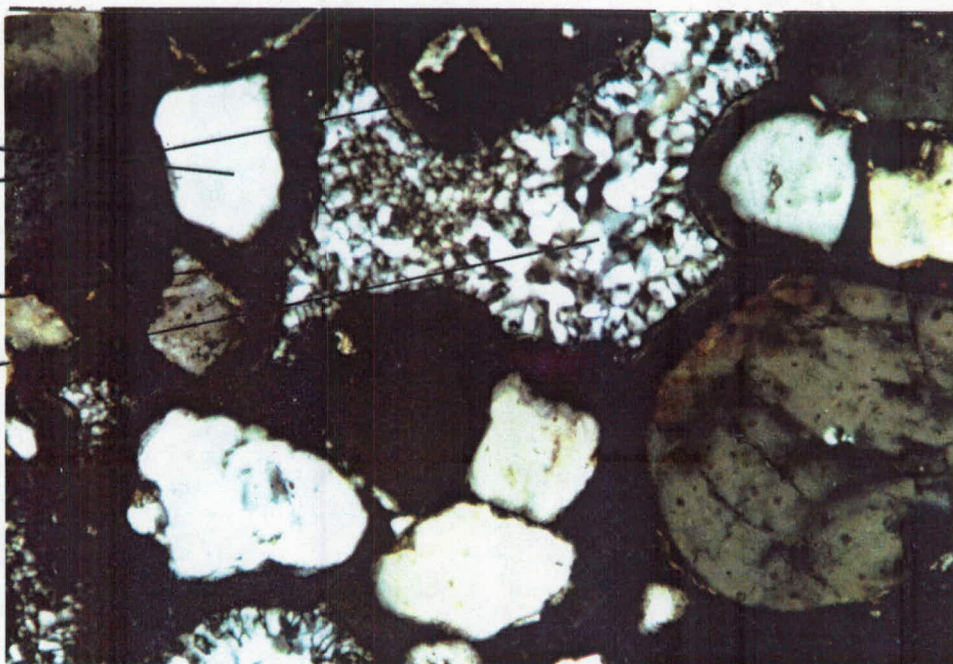
Crossed-polarized light (XPL)

Quartz

Opaque heavy mineral

Calcium carbonate (Micrite)

Silica (Chalcedony)



0.5 mm

**Plate 27**

Sample: PdP/BK/L3

Plane-polarized light (PPL)

Quartz

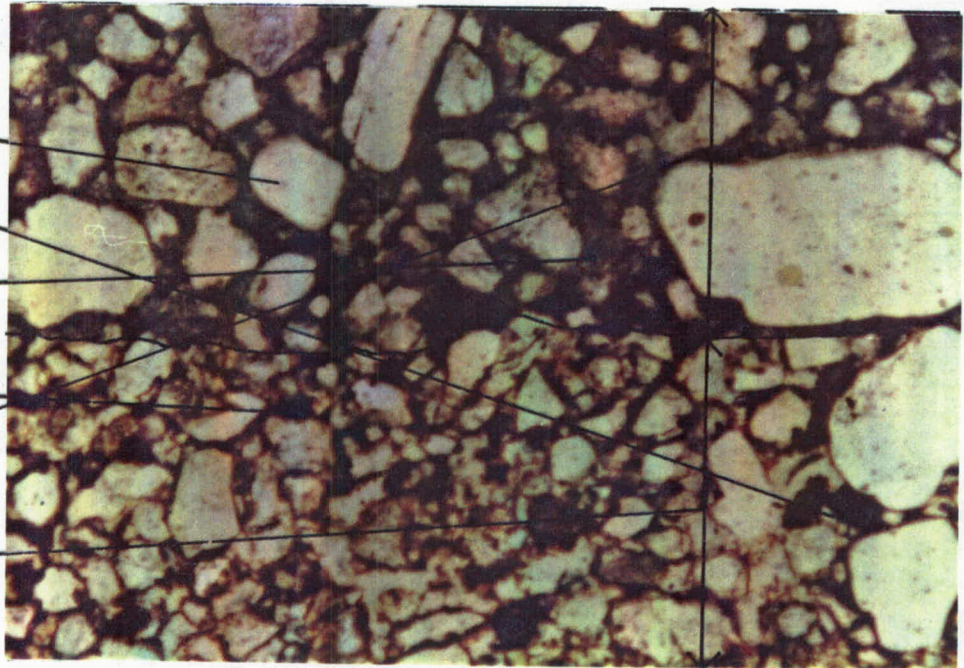
Opaque heavy mineral

Calcium carbonate (Micrite)

Iron oxide

Backfilled burrow

Sediment



0.5 mm



**Plate 28**

Sample: PdP/L/1.4

Plane-polarized light (PPL)

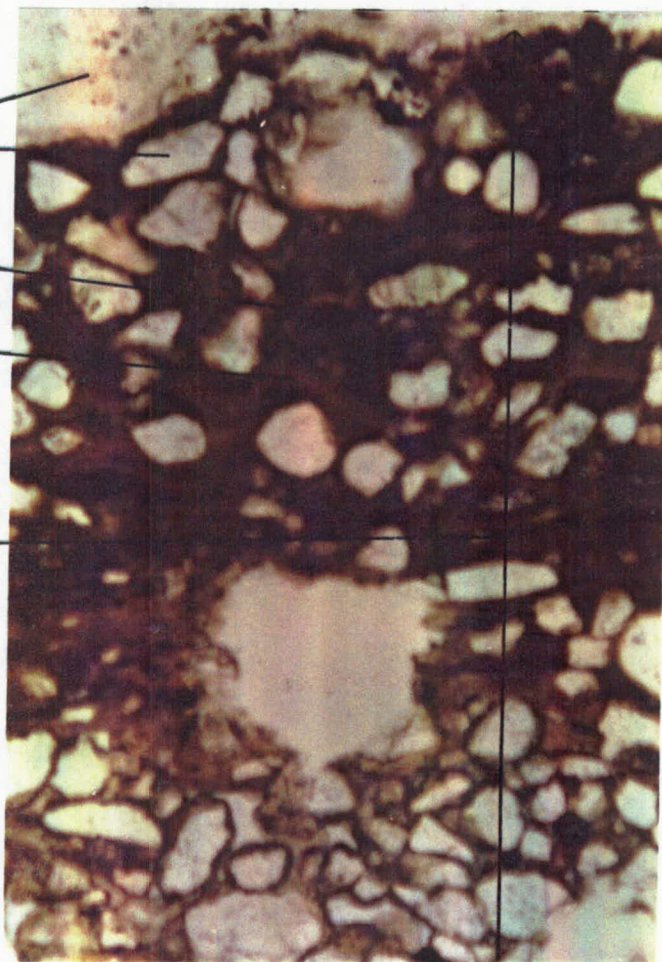
Quartz

Opaque heavy mineral

Glauconite-rich clay  
(green colour in the hand specimen)

Chert

Green sandstone



0.5 mm



**Plate 29**

Sample: PdP/L/14

Crossed-polarized light (XPL)

Quartz

Opaque heavy mineral

Glauconite-rich clay  
(green colour in the hand specimen)

Chert

**Green sandstone**



0.5 mm

**Plate 30**

Sample: PdP/L/L4

Crossed-polarized light (XPL)

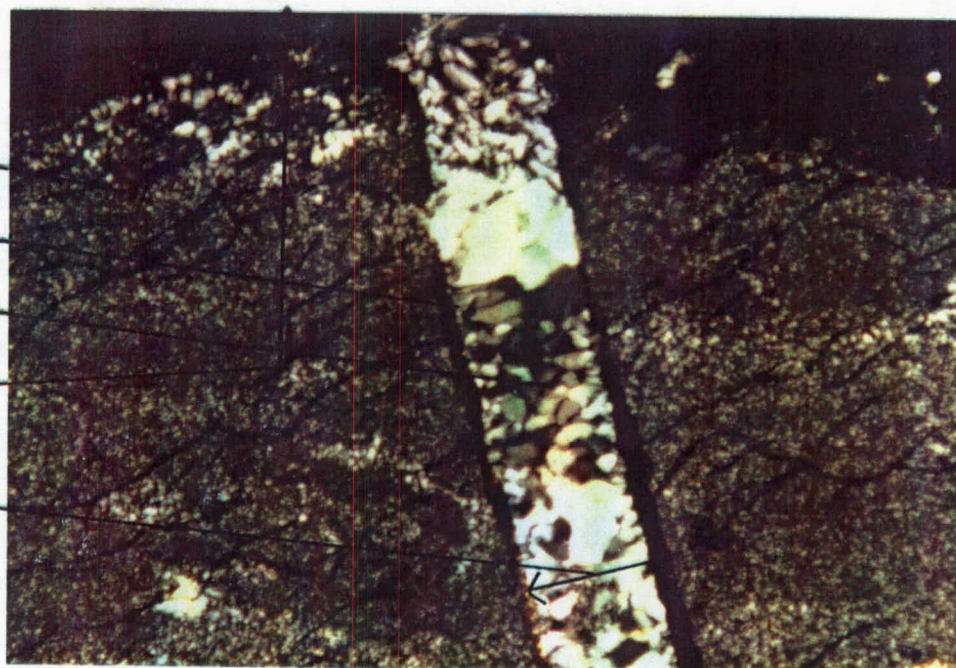
Chert

Iron oxide

Silica (Chalcedony)

Top surface of the chert

Dessication crack



0.5 mm



**Plate 31**

Sample: PdP/L/III

Plane-polarized light (PPL)

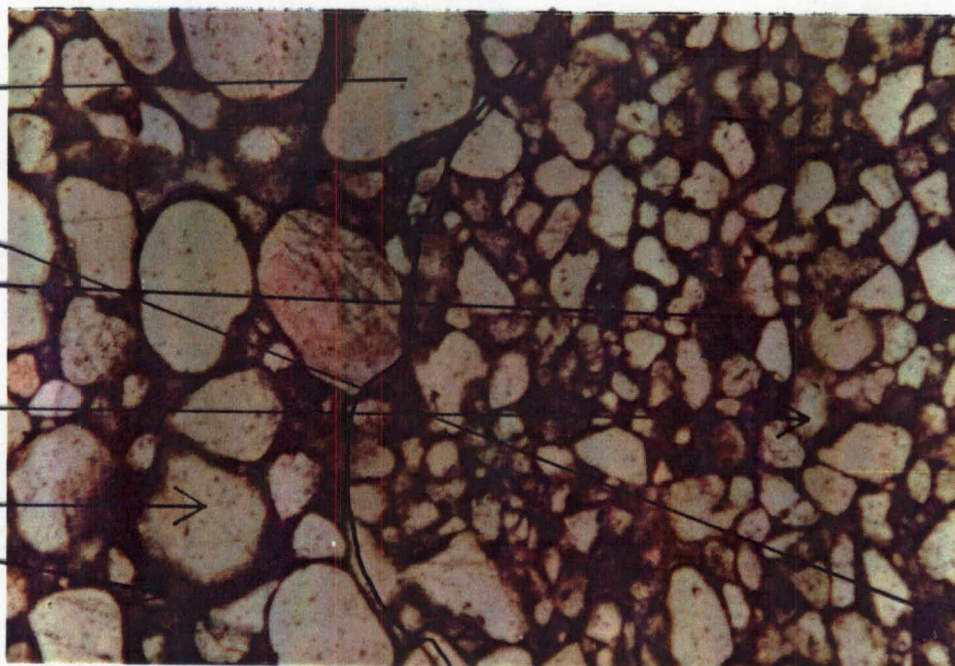
Quartz

Opaque heavy mineral

Glauconite-rich clay minerals  
(Green in hand specimen)

Backfilled burrow

Sediment



0.5 mm

**Plate 32**

Sample: PdP/BK/C4

Plane-polarized light (PPL)

Quartz

Opaque heavy mineral

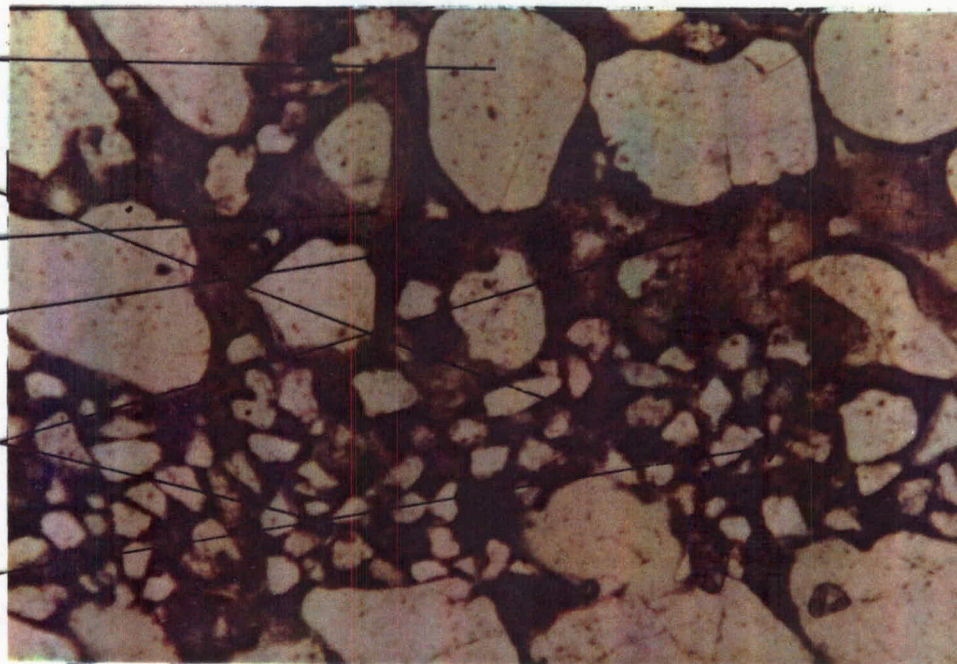
Calcium carbonate (Micrite)

Silica (Chalcedony)

Carbonate-rich clay minerals

Lamina 1

Lamina 2



0.5 mm

**Plate 33**

Sample: PdP/JPLR/LK/Hill/Strom 2

Plane-polarized light (PPL)

Quartz

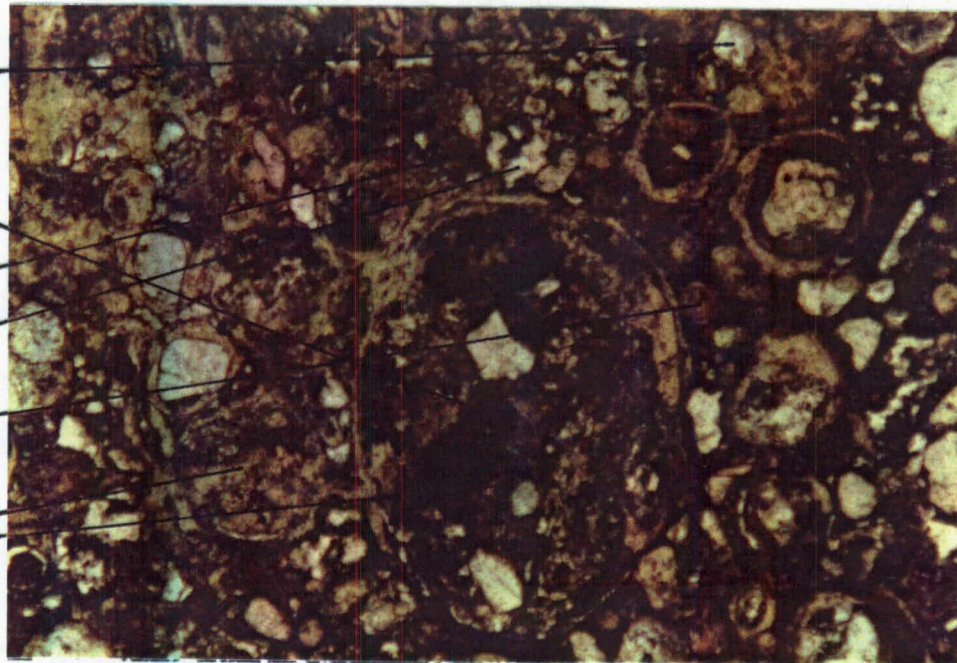
Opaque heavy mineral

Calcium carbonate (Micrite)

Silica (Chalcedony)

Peloid

Fossil algae



0.5 mm



**Plate 34**

Sample: PdP/BK/Ni

Crossed-polarized light (XPL)

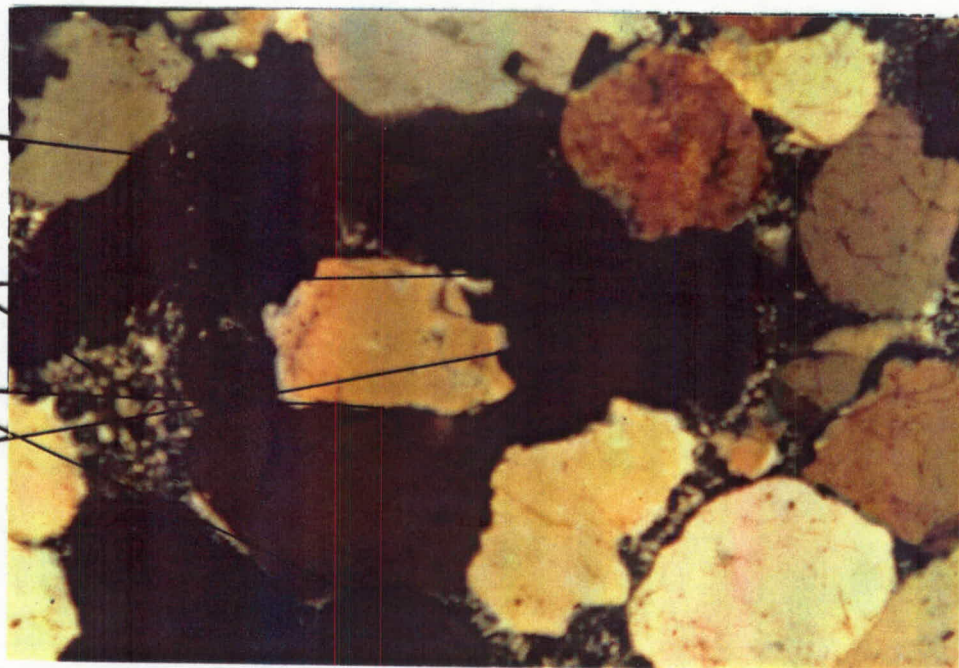
Quartz

Silica (Chalcedony)

Clay minerals

Concavo-convex contacts

Sutured contact



0.5 mm

## Plate 35

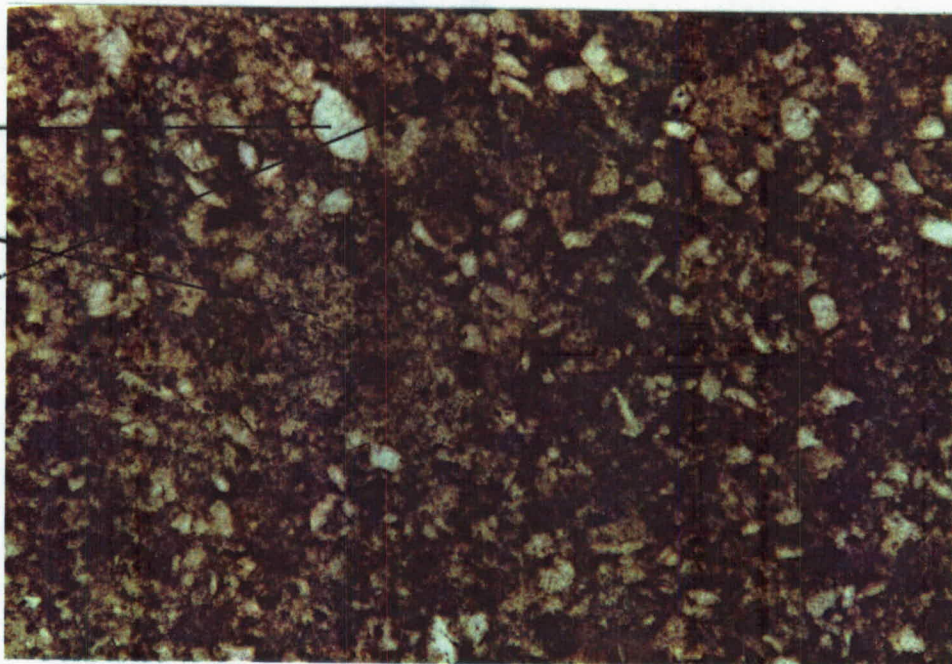
Sample: PdP/JPLR/Mos/LS

Plane-polarized light (PPL)

Quartz

Glaucanite-rich silt and clay

Opaque heavy mineral



0.25 mm

(15) APPENDIX 1THIN SECTION STUDY

A total of 21 thin sections studied with the aid of a petrographic microscope are described below. The Folk (1974) classification was used for the sandstones (Fig. 26) and the Dunham (1962) classification was used for the limestone (Fig. 27). For the grain size classification of the sediments, the Udden-Wentworth scale (Fig. 28) was used.

Sample: PdP/BK/L1

Description and location: Early Kalahari oxidized sandstone at A (Mmashoro Formation) (Orapa-Letlhakane Area).

Hand Specimen: Reddish brown, fine- to medium-grained, moderately bioturbated sandstone. The back-filled burrows are greyish brown in colour.

Thin section:

- (1) Grain size: Grain sizes range from coarse sand to clay.
- (2) Roundness: More than 80 percent of the medium to coarse quartz grains are rounded to sub-rounded, with about 60 percent of the smaller sand grains sub-angular to angular.
- (3) Sphericity: Sphericity ranges from sub-prismoidal to sub-discoidal.
- (4) Sorting: Sorting is moderate to poor.

Principal minerals:

Visual estimate  
of percentage:

(1) Quartz	85
(2) Carbonate-rich mud	11

Other minerals:

(1) Carbonate cement (micrite)	3
(2) Opaque heavy minerals	0.5
(3) Tourmaline	0.1
(4) Zircon	0.1
(5) Iron-oxides	0.2
(6) Chalcedony	0.1

Classification:

Sub-litharenite

History:

The well rounded to rounded quartz grains all have iron-oxide coatings. This is an indication of sub-aerial exposure or shallow water conditions. The *Thalassinoides* trace fossils, however, strongly suggest shallow lacustrine conditions.

The greater amount of iron-oxides in the back-filled burrows may be due to weathering. The greater permeability provided by the burrows facilitates the penetration of oxidized water into the sediment.

The carbonate cement is considered to be a diagenetic feature, chemically precipitated from the groundwater. The carbonate cement forms continuous overgrowths on some of the grains. Silica, in the form of chalcedony, filled in the remaining voids (Plates 25 and 26).

The sediment is considered to be sub-mature.

Sample: PdP/BK/L2

Description and location: Early Kalahari oxidized sandstone at A (Orapa-Letlhakane Area), slightly higher in the sequence than PdP/BK/L1 (Mmashoro Formation).

Hand Specimen: Pale yellow to reddish brown, fine- to medium-grained, moderately bioturbated sandstone. The back-filled burrows are greyish brown in colour. The sandstone has a mottled appearance due to the bioturbation.

Thin section:

- (1) Grain size: Grain sizes range from coarse sand to clay.
- (2) Roundness: More than 80 percent of the medium to coarse quartz grains are rounded to sub-rounded, with about 60 percent of the smaller sand grains sub-angular to angular.
- (3) Sphericity: Sphericity ranges from sub-prismoidal to sub-discoidal.
- (4) Sorting: Sorting is moderate to poor.

Principal minerals:

Visual estimate  
of percentage:

- |                        |      |
|------------------------|------|
| (1) Quartz             | 85   |
| (2) Carbonate-rich mud | 12.2 |

Other minerals:

- |                                |     |
|--------------------------------|-----|
| (1) Carbonate cement (micrite) | 1.8 |
| (2) Opaque heavy minerals      | 0.4 |
| (3) Tourmaline                 | 0.1 |
| (4) Zircon                     | 0.2 |
| (5) Iron-oxides                | 0.3 |

Classification:

Sub-litharenite

History:

The "History" of this sample is identical to the one described on page 87.



**Sample:** PdP/BK/L3

Description and location: Early Kalahari oxidized sandstone at A (Orapa-Letlhakane Area), slightly higher in the sequence than PdP/BK/L2 (Mmashoro Formation).

Hand Specimen: Reddish brown, fine- to medium-grained, moderately bioturbated sandstone. The back-filled burrows are grey in colour. The sandstone has a mottled appearance due to the bioturbation.

**Thin section:**

- (1) Grain size: Grain sizes range from coarse sand to clay.
- (2) Roundness: More than 80 percent of the medium to coarse quartz grains are rounded to sub-rounded, with about 60 percent of the smaller sand grains sub-angular to angular.
- (3) Sphericity: Sphericity ranges from sub-prismoidal to sub-discoidal.
- (4) Sorting: Sorting is moderate to poor.

**Principal minerals:**

	Visual estimate of percentage:		Visual estimate of percentage:
<u>In sediment:</u>		<u>In burrow:</u>	

(1) Quartz	95	80
------------	----	----

**Other minerals:**

(1) Carbonate cement (micrite)	0.1	14.9
(2) Opaque heavy minerals	0.4	1
(3) Tourmaline	0	0.1
(4) Zircon	0.5	4
(5) Iron-oxides	4	0

Classification:

Sub-litharenite

History:

The "history" of this sample is identical to the one described on page 87, except for the following:

The absence of iron-oxides in the in-filled burrows and presence of iron-oxides in the surrounding sediment indicates that the bioturbation took place under wet, possibly deeper water conditions (Plate 27).

Bioturbation was also more intensive than in PdP/BK/L2 (probably also due to the prevailing wetter conditions). On macroscopic as well as microscopic scale, the sharp edges of burrows, supporting the interpretation of bioturbation during a wet period, can clearly be seen. The burrows contain much more heavy minerals, especially zircon, than the surrounding sediment.

The abundant calcium carbonate in the burrows may either be the result of the downward percolation of the overlying calcium carbonate-rich water at the time of bioturbation or due to easier movement of carbonate-rich groundwater in the burrows during diagenesis.

The sandstone is more mature than PdP/BK/L1 and PdP/BK/L2.

**Sample:** PdP/L/L4

**Description and location:** Early Kalahari lacustrine rhythmite at A (Orapa-Letlhakane Area), slightly higher in the sequence than PdP/BK/L3 (Mmashoro Formation).

**Hand Specimen:** Pale green and black layered rhythmite. The pale green layers consist of fine-grained sandstone while the black layers consist of chert.

**Thin section:**

(1) **Grain size:** The sandstone contains medium to very fine sand and mud.

(2) **Roundness:** More than 80 percent of the medium quartz grains are rounded to sub-rounded, with about 60 percent of the smaller sand grains sub-angular to angular.

(3) **Sphericity:** Sphericity of the sandstone grains ranges from prismoidal to discoidal.

(4) **Sorting:** Sorting is moderate to good in the sandstone.

Principal minerals:

<u>In sandstone:</u>	Visual estimate of percentage:	<u>In chert:</u>	Visual estimate of percentage:
(1) Quartz	60		0.7
(2) Chert	0.5		96
(3) Glauconite-rich clay	38.8		0.1

Other minerals:

(1) Chalcedony	0	2.9
(2) Opaque heavy minerals	0.5	0.2
(3) Tourmaline	0.1	0.05
(4) Zircon	0.1	0.03
(5) Iron-oxides	0	0.02

Classification:

Rhythmite

History:

The well rounded to rounded quartz grains all have iron-oxide coatings. This is an indication of sub-aerial exposure or shallow water conditions. The rhythmites are interpreted to be shallow ephemeral lake deposits.

See detailed description of rhythmites in text and plates 28, 29 and 30.

The sediment as a whole is considered to be sub-mature.

Sample: PdP/L/L5

Description and location: Early Kalahari, matrix-supported, silcreted breccia at A (Orapa-Letlhakane Area), at the top of the sequence (Mmashoro Formation).

Hand Specimen: Matrix-supported, silcreted breccia with angular to sub-angular clasts of greyish black chert in a reddish brown sandstone matrix.

Thin section:

- (1) Grain size: Chert pebbles up to 20 mm (longest axis). The matrix consists of coarse to very fine sand.
- (2) Roundness: In the sandstone, more than 80 percent of the medium to coarse quartz grains are rounded to sub-rounded, with about 60 percent of the smaller sand grains sub-angular to angular. The chert clasts are angular to sub-rounded.
- (3) Sphericity: The chert clasts are prismoidal to discoidal, while the grains of the matrix are sub-prismoidal to sub-discoidal.
- (4) Sorting: The matrix is well sorted, but the sediment as a whole is poorly sorted.

Principal minerals:

Visual estimate  
of percentage:

(1) Quartz	30
(2) Chert	50
(3) Chalcedony cement	16.8

Other minerals:

(1) Plagioclase	1
(2) Opaque heavy minerals	0.5
(3) Tourmaline	0.2
(4) Zircon	0.5
(5) Iron-oxides	0.5
(6) Calcium carbonate	0.5



Classification:

Chert conglomerate

History:

The former top surfaces of the chert can be recognized from the desiccation cracks. The chalcedony cement shows perpendicular growth off grain and clast surfaces. Iron oxide-rich calcium carbonate forming continuous overgrowths on grains and clasts, as well as part of the matrix, indicates sub-aerial exposure during or immediately after deposition, or at least shallow water conditions. The chalcedony cement filled in the remaining voids.

The sediment is considered to be a fluvial conglomerate, caused by a wet episode that resulted in erosion of the underlying layered chert deposits. The angular nature of the chert clasts may indicate the relative short distances of transport for these clasts. Alternatively, with desiccation and redeposition of silica in cracks, followed by expansion during wet periods, a breccia can develop from tepee structures.

The silica (chalcedony) cement probably developed in the subsequent quiet lake conditions with intense evaporation that raised the pH and caused silica to firstly go into solution and secondly to precipitate. The chalcedony could also be the result of diagenesis. The plagioclase is probably derived from the underlying Karoo basalts.

The sediment is considered to be immature.

Sample: PdP/L/H1

Description and location: Early Kalahari, pale green, fine- to medium-grained lacustrine sandstone at C (Mmashoro Formation) (Orapa-Letlhakane Area).

Hand Specimen: Pale green, silcreted, fine- to medium-grained, moderately bioturbated lacustrine sandstone. The backfilled burrows show white to grey colours.

Thin section:

(1) Grain size: In the sandstone the grain size ranges from coarse sand to mud, while the trace fossils are backfilled with fine sand.

(2) Roundness: In the sandstone, more than 80 percent of the medium to coarse quartz grains are rounded to sub-rounded, with the rest sub-angular to angular. In the burrows the grains are sub-angular to angular.

(3) Sphericity: The grains are sub-prismoidal to sub-discoidal, but sub-prismoidal to spherical in the burrows.

(4) Sorting: The sandstone is moderately sorted while the backfilled burrows have a well sorted to very well sorted fine sand fraction supported by a clay-rich matrix.

Principal minerals:

<u>In sandstone:</u>	Visual estimate of percentage:	<u>In burrow:</u>	Visual estimate of percentage:
(1) Quartz	90		85
(2) Glauconite-rich clay	6		14.4

Other minerals:

(1) Chalcedony	0.4	0
(2) Opaque heavy minerals	0.5	0.5
(3) Rock fragments	0.2	0.1
(4) Calcium carbonate	0.5	0
(5) Plagioclase	1.3	0

Classification:

Sub-litharenite

History:

The most significant features of this sandstone are the green colour due to the presence of glauconite and the lack of iron-oxides in the sediment. These features indicate deposition under water in a slightly reducing environment.

Also significant is the difference between the grain sizes, roundness and sorting in the backfilled burrows and the sandstone (Plate 31).

The grains in the burrows are orientated parallel to the long edges of the oval cut through the burrow in the thin section. The immature nature and orientation of the sediment in the burrows can either be the result of:

- (1) the mixing of immature sediment above or below the sandstone bed through bioturbation and the backfilling action of the organism or,
- (2) the orientated backfill represents excrement from the organism that fed exclusively on the fine sand and clay fractions.

The calcium carbonate, in the form of sparite, forms continuous overgrowths, with crystal growth perpendicular to the grain surfaces. The carbonate replaces the clay minerals in part. The remaining voids are filled in by silica in the form of chalcedony. The calcium carbonate and chalcedony are considered diagenetic features.

The basaltic rock fragments and plagioclase indicate that the underlying Karoo basalt formed at least part of the provenance.

The sediment is sub-mature with 6 percent clay.

Sample: PdP/L/H2

Description and location: Early Kalahari, pale green, fine- to medium-grained lacustrine sandstone at C (Orapa-Letlhakane Area), slightly higher in the sequence than PdP/L/L1 (Mmashoro Formation).

Hand Specimen: Pale green, silcreted, fine- to medium-grained, moderate to strongly bioturbated lacustrine sandstone. The backfilled burrows show white to grey colours.

Thin section: (No trace fossil in the thin section)

(1) Grain size: A small number (about 10 percent) of the grains are in the coarse and medium size range, with the rest fine sand to mud.

(2) Roundness: The coarse and medium grains are sub-rounded, with the rest sub-angular to angular.

(3) Sphericity: The coarse and medium grains are sub-prismoidal to spherical and the smaller grains are prismoidal to sub-discoidal.

(4) Sorting: The sandstone is moderately sorted.

Principal minerals:

<u>In sandstone:</u>	Visual estimate of percentage:
----------------------	-----------------------------------

(1) Quartz	90
(2) Glauconite-rich clay	6

Other minerals:

(1) Plagioclase	2
(2) Chalcedony	0.3
(3) Opaque heavy minerals	0.6
(4) Zircon	0.3
(5) Tourmaline	0.1
(6) Calcium carbonate	0.7

Classification:

Sub-litharenite

History:

As was the case with sample PdP/L/H1, this sample contains glauconite which suggests deposition under slightly reducing conditions.

The sediment as a whole is finer-grained than PdP/L/L1. This is probably the result of lower energy conditions during

deposition. The angular nature of the majority of the grains as well as the presence of plagioclase suggest relative short distances of transport with the underlying Karoo basalt forming at least part of the source area.

The calcium carbonate, in the form of sparite, forms continuous overgrowths, with crystal growth perpendicular to the grain surfaces. The carbonate replaces the clay minerals in part and also corrodes some of the quartz grains. The remaining voids are filled in by silica in the form of chalcedony. The calcium carbonate and chalcedony are considered to be diagenetic features.

The sediment is sub-mature with 6 percent clay.



Sample: PdP/BK/C1

Description and location: Matrix-supported conglomerate overlying the Karoo basalt at C (Dikara Member) (Mmashoro Formation) (Mmashoro Area).

Hand Specimen: Light brown, matrix-supported conglomerate with dark grey calcrete clasts.

Thin section:

(1) Grain size: The clasts range from pebbles (largest clast = 20 mm) to very fine sand in the matrix.

(2) Roundness: The large calcrete clasts are angular to sub-rounded. About 15 percent of the matrix consists of medium to coarse quartz grains that are rounded to sub-rounded, with the rest of the grains sub-angular to angular.

(3) Sphericity: The clasts range from sub-discoidal to prismoidal.

(4) Sorting: The conglomerate is poorly sorted.

Principal minerals:

Visual estimate  
of percentage:

(1) Quartz	54
(2) Calcrete clasts	40

Other minerals:

(1) Plagioclase	2
(2) Hypersthene	2
(3) Opaque heavy minerals	0.1
(4) Zircon	0.05
(5) Tourmaline	0.05
(6) Calcium carbonate	1.5
(7) Rock fragments	0.1
(8) Augite	0.1
(9) Iron oxides	0.1

Classification:

Matrix-supported conglomerate

History:

The calcrete clasts (consisting of a mixture of sparite and micrite) are derived from the Kwari Formation that covered the top of the Drakensberg basalt. In some places the calcrete is not completely eroded away and can be seen in situ. The calcrete clasts contain a few scattered, angular to sub-angular

quartz grains, some ultra-stable, rounded tourmaline grains as well as some rounded opaque heavy minerals. All of these grains in the calcrete have coatings of iron-oxides that possibly indicate sub-aerial exposure prior to cementation by the calcrete.

The matrix can be considered immature due to the presence of plagioclase, basaltic rock fragments, hypersthene and augite derived from the underlying basalt. The majority of the sediment constituents have apparently not been transported very far and are locally derived. The sediment is therefore considered immature.

The iron-oxide in the matrix indicates sub-aerial exposure of the conglomerate. The diagenetic, sparite cement has not only replaced the clay minerals in the matrix completely, but has even corroded some of the quartz grains.

**Sample: PdP/BK/C2**

**Description and location:** Light brown, fine- to medium-grained, fluvial sandstone with some bioturbation, overlying the basal conglomerate (sample PdP/BK/C1) at C (Mmashoro Formation) (Mmashoro Area).

**Hand Specimen:** Light brown, fine- to medium-grained, fluvial sandstone with some bioturbation. Most of the burrows are backfilled and are whitish grey in colour.

**Thin section:**

- (1) **Grain size:** The grain size ranges from coarse sand to mud.
- (2) **Roundness:** About 15 percent of the grains consists of medium to coarse quartz grains that are rounded to sub-rounded, with the rest of the grains sub-angular to angular.
- (3) **Sphericity:** The clasts range from sub-discoidal to prismatic.
- (4) **Sorting:** The sandstone is moderately sorted.

**Principal minerals:**

In sandstone:	Visual estimate of percentage:
(1) Quartz	85
(2) Clay minerals	6.8

**Other minerals:**

(1) Plagioclase	2
(2) Hypersthene	0.5
(3) Opaque heavy minerals	0.3
(4) Zircon	0.1
(5) Tourmaline	0.05
(6) Calcium carbonate	4
(7) Rock fragments	1
(8) Augite	1
(9) Iron oxides	0.1
(10) Calcrete clasts	0.1

Classification:

Sub-litharenite

History:

See pages 63 and 100.

Sample: PdP/BK/C3

Description and location: Light brown, fine- to medium-grained, fluvial sandstone with some red silt-filled bioturbation burrows, overlying the red sandy clay bed that in turn overlies the bed from which sample PdP/BK/C2 was taken at C (Mmashoro Formation) (Mmashoro Area).

Hand Specimen: Light brown, fine- to medium-grained, fluvial sandstone with some bioturbation. Most of the burrows are backfilled by red sandy mud, similar in appearance to the underlying bed. The sandstone also shows mud rip-up clasts eroded from the underlying bed.

Thin section:

- (1) Grain size: The grain size ranges from coarse sand to mud.
- (2) Roundness: About 15 percent of the grains consist of medium to coarse quartz. These are rounded to sub-rounded, with the rest of the grains sub-angular to angular.
- (3) Sphericity: The clasts range from sub-discoidal to prismatic.
- (4) Sorting: The sandstone is moderately to poorly sorted.



Principal minerals:

In sandstone:                      Visual estimate  
   of percentage:

(1) Quartz	85
(2) Clay minerals	9

Other minerals:

(1) Plagioclase	1
(2) Hypersthene	0.5
(3) Opaque heavy minerals	0.5
(4) Zircon	0.1
(5) Tourmaline	0.1
(6) Calcium carbonate	3.2
(7) Augite	0.4
(8) Iron oxides	0.1
(9) Calcrete clasts	0.1

Classification:

Sub-litharenite

History:

From the bottom to the top of Profile C (Mmashoro Area), there is a decrease in the size as well as the number of clasts derived from the Karoo basalt and Kwari Formation. The roundness and sphericity of these basaltic and calcrete clasts increase to the top. In this sample (PdP/BK/C3) no more basaltic rock fragments were seen.

As was the case in the previous two samples, the calcrete clasts are derived from the Kwari Formation that covered the top of the Drakensberg basalt.

The matrix can still be considered immature due to the presence of plagioclase, hypersthene and augite derived from the underlying basalt.

The sediment contains more clay than sample PdP/BK/C2 as it eroded a sandy clay bed as can be seen from the mud rip-up clasts. Also see page 63.

**Sample:** PdP/JPLR/5 and PdP/BK/C4

**Description and location:** Light brown, fine- to medium-grained, trough cross-bedded, fluvial sandstone with some bioturbation burrows, forming the topmost bed of the profile at C (Mmashoro Formation) (Mmashoro Area).

**Hand Specimen:** Light brown, fine- to medium-grained, cross-bedded, fluvial sandstone with some bioturbation.

**Thin section:**

(1) **Grain size:**

Lamina 1: The grain size ranges from coarse to medium sand.  
Lamina 2: The grain size ranges from fine sand to mud.

(2) **Roundness:**

Lamina 1: The grains are well rounded to sub-rounded.  
Lamina 2: The grains are angular to sub-rounded.

(3) **Sphericity:**

Lamina 1: The grains range from sub-discoidal to sub-prismoidal.  
Lamina 2: The grains range from prismoidal to discoidal.

(4) **Sorting:**

Lamina 1: The sandstone is very well sorted.  
Lamina 2: The sandstone is well sorted.

Principal minerals:

<u>In lamina 1:</u>	Visual estimate of percentage:	<u>In lamina 2:</u>	Visual estimate of percentage:
(1) Quartz	90	85	
(2) Calcium carbonate	6.9	2	

Other minerals:

(1) Plagioclase	0.5	1
(2) Hypersthene	0.1	0.6
(3) Opaque heavy minerals	0.1	0.1
(4) Chalcedony	1.9	0.1
(5) Tourmaline	0.1	0.2
(6) Clay minerals	0.1	10
(7) Augite	0.1	0.7
(8) Iron oxides	0.1	0.1
(9) Calcrete clasts	0.1	0.2

Classification:

Sub-litharenite

History:

The trough cross-bedded sandstone shows laminae of coarser grains alternating with laminae of finer grains (Plate 32). The coarser-grained laminae, because of better permeability, show more pore filling by the sparite and chalcedony cement. Calcium carbonate in the form of sparite forms continuous overgrowths and perpendicular growth off grain surfaces, with the remaining voids being filled in by silica in the form of chalcedony. The finer-grained, clay-rich laminae, with lower permeability, have less sparite and chalcedony.

From the base to the top of Profile C (Mmashoro Area), there is a decrease in the size as well as the number of clasts derived from the Karoo basalt and Kwari Formation. The roundness and sphericity of these basaltic and calcrete clasts increase to the top.

The calcrete clasts are derived from the Kwari Formation that covered the top of the Drakensberg basalt. Where the calcrete is not completely eroded away it can be seen in situ. As described on page 100, the calcrete clasts contain quartz and tourmaline grains as well as some opaque heavy minerals.

The iron-oxide in the matrix indicates shallow water conditions or sub-aerial exposure of the sandstone. The diagenetic, sparite cement has replaced some of the clay minerals in the matrix. The clay minerals are interpreted to be largely a weathering product of the Karoo basalt. The majority of the sediment constituents have not been transported very far and are locally derived. The sediment is however much more mature than the basal conglomerate (PdP/BK/C1) and as a whole is considered sub-mature. The basaltic source for a large number of the grains can still be recognized from the grain composition.

Sample: PdP/BK/B1

Description and location: Early Kalahari, pale yellow to grey, fine- to medium-grained, strongly bioturbated lacustrine sandstone, one metre above the basal contact with the Karoo basalt at B2 (Mmashoro Formation) (Mmashoro Area).

Hand Specimen: Mottled, pale yellow to grey, fine- to medium-grained, strongly bioturbated, lacustrine sandstone. The backfilled trace fossils are grey in colour, while the sediment is pale yellow in colour.

Thin section:

- (1) Grain size: The grain size ranges from coarse sand to mud.
- (2) Roundness: About 5 percent of the grains consist of coarse to medium quartz grains that are rounded to sub-rounded, with the rest of the grains sub-rounded to angular.
- (3) Sphericity: The grains range from spherical to prismoidal.
- (4) Sorting: The sandstone is moderately to well sorted.

Principal minerals:

Visual estimate  
of percentage:

- |                       |    |
|-----------------------|----|
| (1) Quartz            | 85 |
| (2) Calcium carbonate | 10 |

Other minerals:

- |                           |     |
|---------------------------|-----|
| (1) Plagioclase           | 1.8 |
| (2) Hypersthene           | 0.1 |
| (3) Opaque heavy minerals | 0.5 |
| (4) Tourmaline            | 0.1 |
| (5) Clay minerals         | 2   |
| (6) Augite                | 0.4 |
| (7) Zircon                | 0.1 |

### Classification:

Sub-litharenite

### History:

The calcium carbonate, in the form of micrite, forms continuous overgrowths on grains, with the remaining voids, in contrast with the fluvial sediments (e.g. PdP/JPLR/5) at C (Mmashoro Area) also being filled in by calcium carbonate, this time in the form of sparite. The diagenetic, calcium carbonate cement has corroded and replaced some of the clay minerals in the matrix.

The absence of iron oxides in the sediment suggests deposition under water, as can be expected in the lacustrine environment.

The strong bioturbation with no iron-oxides in the burrows also suggests the inundation of the sediments during bioturbation. The bioturbation in these lacustrine sediments was much more intense than in the sub-aerially exposed, higher energy, fluvial sediments at Profile C (Mmashoro Area).

From the base to the top of the lacustrine succession at B1 and B2, there is a decrease in the size as well as the number of clasts derived from the Karoo basalt (section 5.5.4). The roundness and sphericity of these basaltic clasts increase to the top. Since the energy of the lacustrine environment at B1 and B2 was much lower than in the fluvial environment of Profile C (Mmashoro Area), the size of the clasts derived from the underlying basalt in the sediments immediately overlying the basalt is much smaller at B2 (Mmashoro Area) than at C (Mmashoro Area). The sandstone grains in general, at B2, are slightly smaller and better sorted than at C (Mmashoro Area).

The basaltic source for a large number of the grains can however, still be recognized from the grain composition.

The sediment is considered to be sub-mature.



**Sample:** PdP/BK/B2

**Description and location:** Early Kalahari, light grey to white, fine- to medium-grained, intensely bioturbated lacustrine sandstone, seven metres above the basal contact with the Karoo basalt at B2 (Mmashoro Formation) (Mmashoro Area).

**Hand Specimen:** Mottled, pale grey to white, fine- to medium-grained, intensely bioturbated, lacustrine sandstone. The backfilled trace fossils are white in colour, while the sediment is pale grey in colour.

**Thin section:**

- (1) **Grain size:** The grain size ranges from coarse sand to mud.
- (2) **Roundness:** About 5 percent of the grains consist of coarse to medium quartz. These are rounded to sub-rounded, with the rest of the grains rounded to sub-angular. The grains are more rounded than those of PdP/BK/B1.
- (3) **Sphericity:** The grains range from spherical to sub-prismoidal, with better sphericities than those of PdP/BK/B1.
- (4) **Sorting:** The sandstone is well sorted, while the backfilled burrows are moderately to poorly sorted. Generally speaking, the sandstone is better sorted than PdP/BK/B1.

Principal minerals:

Visual estimate  
of percentage:

(1) Quartz	90
------------	----

Other minerals:

(1) Plagioclase	1
(2) Hypersthene	0.05
(3) Opaque heavy minerals	0.3
(4) Tourmaline	0.1
(5) Clay minerals	0.5
(6) Augite	0.05
(7) Zircon	0.1
(8) Calcium carbonate	3
(9) Chalcedony	4.9

Classification:

Sub-litharenite

History:

The calcium carbonate, in the form of micrite, forms continuous overgrowths on grains, with the remaining voids being filled in by chalcedony. The diagenetic, calcium carbonate cement has corroded and replaced some of the clay minerals in the matrix. The silica cement (chalcedony) has in some places completely replaced both the clay minerals and the carbonate (micrite) cement.

Once again there is an absence of iron oxide in the sediment which suggests deposition under water, as can be expected in the lacustrine environment. There is also a lack of iron oxides in the burrows as described on page 110.

A basaltic source for large numbers of the grains can still be recognized from the grain composition.

The sediment is considered to be mature.

Samples: PdP/JPLR/LK/Hill/Strom 1 + PdP/JPLR/LK/Hill/Strom 2 + PdP/JPLR/LK/Hill/LS

Description and location: Early Kalahari, light brown, fine- to medium-grained, sandstone and stromatolites, at the top of the lacustrine succession at B1 (Mmashoro Formation) (Mmashoro Area).

Hand Specimen: Light brown, fine- to medium-grained, small (4 cm high with a 10 cm diameter) mound-like, laminated stromatolite.

Thin section:

- (1) Grain size: The grain size ranges from fine to medium sand with micrite.
- (2) Roundness: The grains are sub-rounded to sub-angular.
- (3) Sphericity: The grains range from sub-discoidal to sub-prismoidal.
- (4) Sorting: The sediment is well sorted.

Principal minerals:

Visual estimate  
of percentage:

- |                |     |
|----------------|-----|
| (1) Micrite    | 90  |
| (2) Chalcedony | 5.6 |

Other minerals:

- |                           |      |
|---------------------------|------|
| (1) Quartz                | 4    |
| (2) Plagioclase           | 0.1  |
| (3) Opaque heavy minerals | 0.1  |
| (4) Tourmaline            | 0.05 |
| (5) Iron-oxides           | 0.1  |
| (6) Zircon                | 0.05 |

Classification:

Stromatolite (boundstone according to the limestone classification of Dunham, 1962).

### History:

Two generations of silica cement in the form of chalcedony can be seen in the thin sections. The first formed continuous colloform overgrowths on grains, (similar to the calcium carbonate in PdP/BK/B2), while the second filled in the remaining voids. It is thought that the first generation of silica precipitated not long after sediment deposition, because the stromatolitic deposits grade laterally into and are overlain by layered chert (silica-rich) deposits. After this first generation of silica precipitation, there was sub-aerial exposure of the sediment or shallow water conditions, resulting in the iron-oxide precipitation on the continuous overgrowths of silica. Silica then filled in the remaining voids.

From the base to the top of the lacustrine succession at B1 and B2, there is a decrease in the size as well as the number of clasts derived from the Karoo basalt. The roundness and sphericity of these basaltic clasts increase to the top. The sandstone grains in general, in PdP/JPLR/Hill/Strom 1, are better sorted than in PdP/BK/B2 and of the grains derived from the Karoo basalt, only small sub-rounded to rounded plagioclase grains remain. PdP/JPLR/Hill/Strom 1 therefore represents a more mature sediment in terms of grain composition.

See also pages 59 to 62.

The sediment is considered to be mature.

Sample: PdP/BK/V1

Description and location: Early Kalahari, light grey to light brown, calcreted Dikara conglomerate, with some bioturbation, overlying pale to dark green siltstones of the Mosolotsane Formation (Karoo age), at P11 (Mmashoro Formation) (South Sua Pan Area).

Hand Specimen: Light grey to light brown, sandy conglomerate. The sediment contains angular to sub-rounded, up to 7 mm long pebbles of the underlying Mosolotsane Formation. Cracks are filled in by calcrete.

Thin section:

- (1) Grain size: The grain size ranges from pebbles to mud.
- (2) Roundness: Grains range from sub-rounded to very angular.
- (3) Sphericity: The grains range from prismoidal to discoidal.
- (4) Sorting: The sandstone is poorly sorted.

Principal minerals:

Visual estimate  
of percentage:

(1) Quartz	61
(2) Green Karoo siltstone	19.7
(3) Muddy (clay) matrix	10
(4) Calcium carbonate	5

Other minerals:

(1) Plagioclase	4
(2) Iron-oxides	0.2
(3) Opaque heavy minerals	0.09
(4) Hypersthene	0.01

Classification:

Conglomerate

### History:

Calcium carbonate in the form of sparite, forms the cement in the conglomerate. The diagenetic, calcium carbonate cement has not only corroded and replaced some of the clay minerals in the matrix, but also corroded the Mosolotsane siltstone clasts, plagioclase and quartz. Calcrete in the form of sparite fills in and probably widened cracks in the sediment through its replacive and displacive effects.

The presence of iron oxide in the sediment suggests sub-aerial deposition, as can be expected in the fluvial environment. The large siltstone clasts in the conglomerate are derived from the underlying green Mosolotsane Formation, which outcrops to the east and west (South Sua Pan Area). The sub-angular plagioclase and hypersthene are probably derived from the Karoo basalt or Post-Karoo dolerite dykes. The immature nature and angularity of the clasts in the sediment suggests a proximal position in the depositional basin.



**Sample:** PdP/Nt/V1

**Description and location:** Karoo Age, grey to reddish brown, fluvial Ntane Formation sandstone that at a first glance, resembles fluvial Kalahari Group sandstones. The sample was taken 2 km north of P 11 along the veterinary cordon fence (South Sua Pan Area).

**Hand Specimen:** Grey to reddish brown, coarse, siliceous sandstone.

**Thin section:**

- (1) **Grain size:** The grain size ranges from very coarse sand to fine sand with some clay.
- (2) **Roundness:** Grains range from well-rounded to sub-angular.
- (3) **Sphericity:** The grains range from sub-prismoidal to sub-discoidal.
- (4) **Sorting:** The sandstone is well to very well sorted.

**Principal minerals:**

Visual estimate  
of percentage:

- |                       |     |
|-----------------------|-----|
| (1) Quartz            | 90  |
| (2) Chalcedony cement | 5.9 |

**Other minerals:**

- |                   |     |
|-------------------|-----|
| (1) Clay minerals | 4   |
| (2) Plagioclase   | 0.1 |

**Classification:**

Sub-litharenite

**History:**

See page 47.

Sample: PdP/JPLR/Mos/LS

Description and location: Dark green, lacustrine siltstone of the Makgadikgadi Subgroup overlying red to pale green siltstone and mudstones of the Thlabala Formation as well as a Post-Karoo dolerite dyke. The sample was taken 1 km north of Mosu village, from an outcrop in Sua Pan (South Sua Pan Area). The outcrop is calcreted and partly overlain by the unconsolidated, recent Sua Pan sediments.

Hand Specimen: Dark green siltstone.

Thin section:

- (1) Grain size: The grain size ranges from coarse silt to clay.
- (2) Roundness: Grains range from sub-rounded to very angular.
- (3) Sphericity: The grains range from prismoidal to spherical.
- (4) Sorting: The sandstone is well sorted.

Principal minerals:

Visual estimate  
of percentage:

- |                          |      |
|--------------------------|------|
| (1) Quartz               | 50   |
| (2) Glauconite-rich clay | 49.4 |

Other minerals:

- |                           |     |
|---------------------------|-----|
| (1) Opaque heavy minerals | 0.5 |
| (2) Muscovite             | 0.1 |

Classification:

Siltstone

History:

The glauconite-rich siltstone represents the lacustrine sediments commonly found in the Makgadikgadi Pans. The angularity of the grains, the good sorting, abundance of glauconite, the presence of muscovite and the large percentage of clays, confirm the low energy lacustrine conditions that prevailed during deposition (Plate 35).